Optimised Biogas Production At Malabar Sewage Treatment Plant

By

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Declaration

This dissertation is an authentic account of original research conducted by me which has not been submitted towards another degree. Editorial changes that were recommended after its examination in November 2010 have been made.

Steven Mark Cowgill

January 2011

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Disclaimer

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Abstract

Methane in biogas from anaerobic digestion of sewage sludge at Malabar Sewage Treatment Plant (STP) fuels a cogeneration system of rated capacity 2,975 kW_E that helps meet the site's electrical load of about 3,600 kW_E. Low biogas flow rates limit the cogeneration system to peak loads of about 2,300 kW_E in a rolling average of 1,900 kW_E. Site operating costs are thus increased by the need to purchase up to 1,000 kW_E of additional grid electricity at any given time.

This research investigated ways to increase the supply of biogas to the cogeneration system. A literature review of anaerobic digestion microbiology and high rate primary sewage treatment processes gave benchmark performance data against which Malabar STP digesters could be compared. Methods of increasing the biogas yield per unit mass of sewage sludge were evaluated for their likely benefit and risk at Malabar STP. The most viable of these were ultrasonic pre-treatment of sludge, food waste co-digestion, and use of mechanical mixers in place of compressed biogas for sludge recirculation. These methods could increase existing steady state biogas flow rates by up to 40%.

It was concluded, however, that methods to increase biogas yield would be unnecessary at Malabar STP if Digester 3 was returned to active sludge digestion, and if the sludge in all digesters was maintained at a constant temperature of 35 ^{o}C ± 0.5 $^{o}C/d$. Under these conditions some 10,300 m^3/d of additional biogas would be produced, enabling the cogeneration system to operate at its rated capacity.

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Definitions

Active volume	Total volume of an anaerobic digester less the volume occupied by accumulated biogas, floating scum, sunken grits, and internal components.
Availability factor	Ratio of the time a power generating system is capable of service during a given period (whether actually used of not) to the total duration of the period.
Capacity factor	Ratio of the actual energy produced by a power generating system during a given period to the energy that would have been produced by continuously operating the system at its rated output during the same period.
Chemical oxygen demand	Mass of oxygen that would be required to oxidise all of the organic compounds present in a unit volume of sewage (in principle the higher the COD the more material is available for biogas production).
Efficiency	Ratio of the energy output of a conversion system to the energy supplied to it.
Hydraulic retention time	Time in days spent by a unit volume of wet sludge inside the active volume of an anaerobic digester; practical retention time for 50 – 60% destruction of volatile solids ranges between 12 and 25 days under mesophilic conditions.
Load factor	Ratio of the average electrical load to the peak electrical load on a power generating system during a given period (normally one year); systems having a higher load factor tend to use their installed capacity more profitably.
Solids retention time	Time in days spent by an equivalent unit mass of 100 %wt (i.e. dry) sludge inside an anaerobic digester.
Sludge	Wet solids content of sewage; it may be further described during treatment as *primary*, *secondary*, *waste activated, dewatered*, etc. according to stages of stabilisation and breakdown.
Standard conditions	Temperature of 20 ^{o}C and pressure of 101.3 kPa.
Volatile solids	The organic fraction of the total solid content of sewage that is substrate for AD bacteria; it is either vaporised or oxidised at temperatures between 500 – 600 ^{o}C leaving behind the *fixed* inorganic solids fraction.

Abbreviations

%vol	Percentage per unit volume of one component in a mixture of gases
%wt	Percentage per unit mass of one component in a single- or multi-phase mixture of solid and liquid substances
^oC	Temperature in degrees Celsius
$^oC/d$	Maximum deviation of constant sludge temperature during 24 hours
$\Delta\%$	Percentage change in an initial quantity
AD	Anaerobic digestion
AT	Aerobic thermophilic
CAS	Chemically assisted sedimentation
CH_4	Methane gas
CO_2	Carbon dioxide gas
COD	Chemical oxygen demand
CSV	Comma separated variable format (of raw data)
GWh_E	Gigawatt hour of electrical energy
GWh_T	Gigawatt hour of thermal energy
HRT	Hydraulic retention time
kg/d	Kilograms per day of mass flow rate
kg/m^3	Kilograms of mass per cubic metre of volume
kg_{VS}/m^3	Kilograms of volatile solids per cubic metre of primary sludge volume
$kg_{VS}/m^3/d$	Kilograms of volatile solids fed per day per cubic metre of digester volume
kGy	Kilogray of absorbed dose by gamma irradiation
kHz	Kilohertz of ultrasound frequency
kPa	Kilopascals of absolute pressure
kPag	Kilopascals of gauge pressure

kW	Kilowatt of mechanical power
kW_E	Kilowatt of electrical power
kWh_E	Kilowatt hour of electrical energy
L/s	Litres per second of liquid or gas flow at operating conditions
m^3	Cubic metres of liquid or gas volume at operating conditions
m^3/d	Cubic metres per day of liquid of gas flow at operating conditions
m^3/kg_{COD}	Cubic metres of biogas or methane per kilogram of digested COD
m^3/kg_{VS}	Cubic metres of biogas or methane per kilogram of digested VS
m^3_{CH4}/m^3	Cubic metres of methane per cubic metre of primary sludge
mg/L	Milligrams concentration per litre in liquid solution
MHz	Megahertz of microwave frequency
MJ/Nm^3	Megajoules of energy per cubic metre of gas at standard conditions
ML/d	Megalitres per day of liquid flow
MW_E	Megawatt of electrical power
OECD	Organisation for Economic Cooperation and Development
OHPA	Obligate hydrogen producing acetogen
P&ID	Process and instrumentation diagram
s	Seconds of time duration
SCADA	Supervisory control and data acquisition (system)
SRB	Sulphate reducing bacteria
SRT	Solids retention time
STP	Sewage treatment plant
SW	Sydney Water
VFA	Volatile fatty acid
VS	Volatile solids
VSLR	Volatile solids loading rate

1. Introduction

This section presents background information on sewage biogas and Malabar Sewage Treatment Plant (STP) in order to set a context for later discussion of findings from the literature review and survey of operating data.

1.1 Sewage Biogas

Biogas, a nominal mixture of 60 %vol methane and 40 %vol carbon dioxide, produced by anaerobic digestion (AD) of sewage sludge in utility digesters, is increasingly viewed as a valuable, renewable fuel for decentralised power generation in urban areas. Power generation is usually accompanied by the recovery of waste thermal energy from engine exhaust gases and cooling systems and its use for process or district heating. Such an arrangement is known as a biogas fired cogeneration system.

In the past sewage biogas has been neglected as a fuel source. To demonstrate this, Table 1.1.1 compares total and per capita electricity generated from sewage biogas in selected OECD countries with their total electricity generated during 2009. These two data sets were derived from the sources listed below Table 1.1.1. Germany leads this field and the world by generating 13 kWh_E per capita from sewage biogas, or roughly 0.2% of total annual electricity consumption. Australia currently generates about 6 kWh_E per capita.

In 2009 Germany had 1,893 MW_E of stationary generating capacity operating on biogas derived from sewage and energy crops (mostly from the latter) and had under construction 1,093 new biogas fired generators of total capacity 516 MW_E (EurObserv'ER 2010). As well as being used in a relatively raw form for generating electricity, purified biogas is sold as a vehicle fuel and also added to the piped natural gas supply across northern Europe. Purifying biogas involves chemical treatment to remove carbon dioxide and trace contaminants, compression to increase energy density, and refrigeration to remove moisture.

Table 1.1.1 Electricity generated from sewage biogas in selected OECD countries during 2009

Country	Total electricity generated (GWh_E) [1]	Electricity generated from sewage biogas (GWh_E) [3]	Population [1]	Electricity from sewage biogas per capita (kWh_E)	Percent of total electricity from sewage biogas (%)
Germany	547,000	1,057	82,217,800	12.9	0.19
Luxembourg	6,500	6	497,500	12.1	0.09
United Kingdom	345,000	638	60,587,000	10.5	0.18
Netherlands	124,000	150	16,639,800	9.0	0.12
Czech Republic	62,000	83	10,256,700	8.1	0.13
United States	3,873,000	2,400 [4]	310,232,800	7.7	0.06
Denmark	34,300	38	5,515,500	6.8	0.11
Australia	222,000	125 [2]	21,515,000	5.8	0.06
Austria	68,300	39	8,214,100	4.7	0.06
Poland	129,300	123	38,463,700	3.2	0.10
Sweden	134,500	19	9,074,100	2.1	0.01
France	447,000	45	63,601,000	0.7	0.01
Italy	315,000	20	59,715,600	0.3	0.01

(Sources: [1] Central Intelligence Agency 2010, [2] Clean Energy Council of Australia 2010, [3] EurObserv'ER 2010, [4] United States Energy Information Administration 2010)

Australia has a total of about 40 MW_E of stationary capacity that generates about 125 GWh_E from sewage biogas (Clean Energy Council of Australia 2010). This is forecast to increase by 2020 to about 900 GWh_E generated from about 120 MW_E of total stationary capacity (Clean Energy Council of Australia 2008). Sewage biogas is classed as a renewable energy source in the legislation governing Australia's mandatory renewable energy target, but its useful conversion is rare, and is limited to a few larger STPs in the major metropolitan areas.

There are novel examples in Australia of small generators operating on non-sewage biogas (from animal manures and organic process wastes) but data on their individual capacities and performance are not generally available.

1.2 Sydney Water

Sydney Water (SW), an enterprise of the New South Wales state government, owns and operates eight biogas fired cogeneration systems across its sewage treatment network within the Sydney metropolitan region. Figure 1.2.1 is a diagram of SW's sewage catchments and STPs.

Central to each SW cogeneration system is an electrical generator driven by a reciprocating spark-ignition engine. The raw biogas supplied from the digesters at low pressure is compressed and dried upstream of the engine's fuel metering system. The systems are configured to supply electricity to the particular STP's main switchboard, thus displacing some – but not replacing all – of the central grid power supply. Heat recovered from the jacket cooling system is used to assist maintain stable temperature in the digesters.

SW's total biogas fired power generation capacity is 7,790 kW_E, which in 2010 is forecast to produce approximately 37.4 GWh_E of electricity and 55 GWh_T of process heating. This is roughly 15% of SW's annual electricity consumption, achieved at a nominal 60% overall conversion efficiency (i.e. including heat recovery).

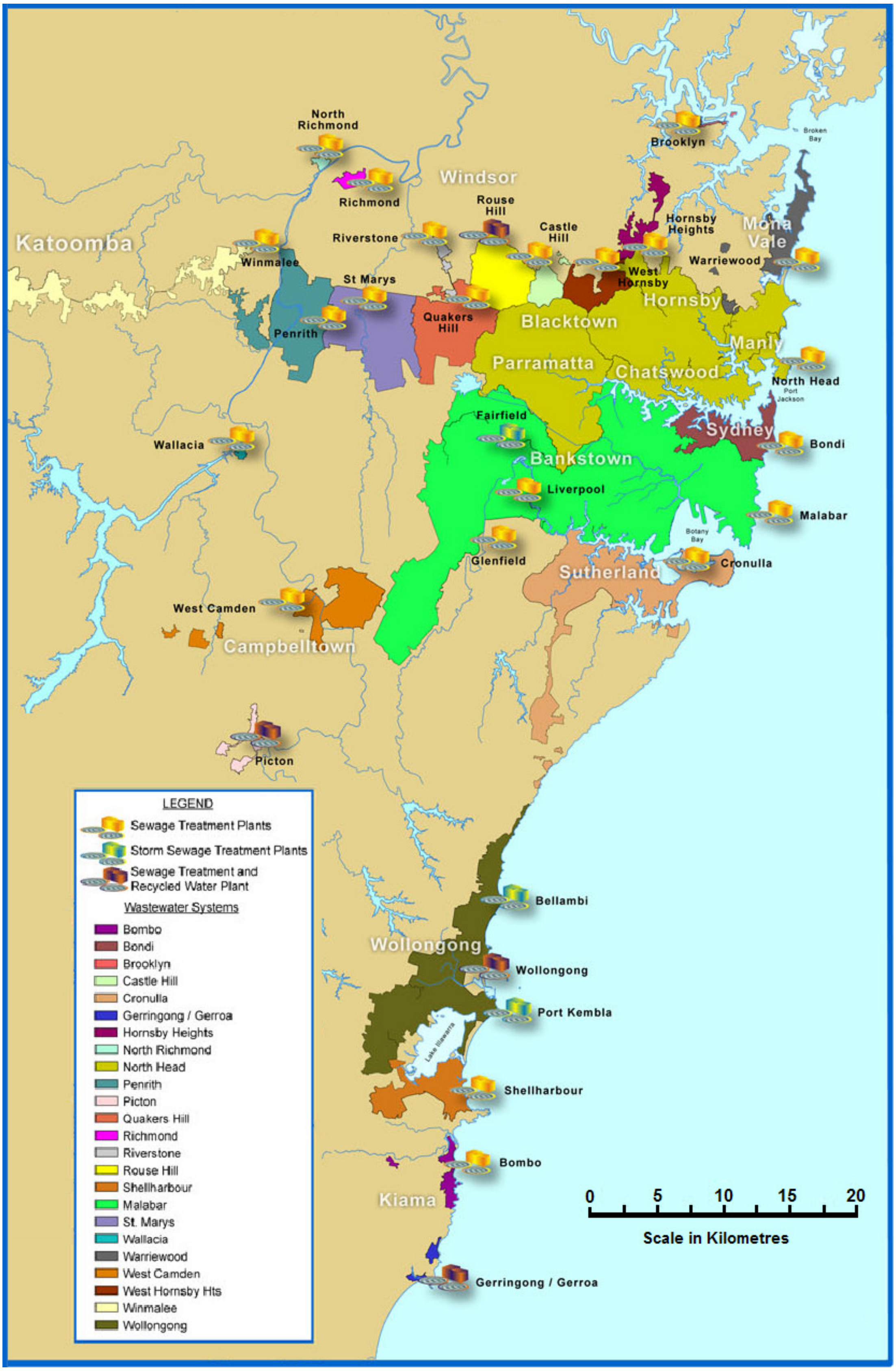


Figure 1.2.1 Sydney Water sewage treatment network

1.3 Malabar STP

Malabar STP began operating in the 1950s and has been expanded in stages since then. It processes an average dry weather flow of 477 ML/d of raw sewage by high rate primary separation, anaerobic sludge digestion, and deep water ocean dispersion of the treated effluent. The influent enters from two trunk mains (SWSOOS 1 and 2) handling the domestic, commercial, and industrial liquid wastes of an urban population of about 1.7 million people across south western Sydney.

Figure 1.3.1 is a process flow diagram showing the treatment stages and by-products at Malabar STP. The influent is first screened to remove bulk solid contaminants such as sticks, rags, and plastics before hard particulates known as grits are removed by cyclonic separators. The influent is then pumped into large sedimentation tanks in which the flow velocity is lowered such that the suspended solids (≤1 %wt at this point) settle under gravity to form primary sludge at the bottom of the tanks. Contaminant oils, fats, and greases float to the surface of the sedimentation tanks and are removed by scum scrapers.

The primary sludge (now approximately 4 %wt of solids) is pumped to the anaerobic digesters. The balance of the treated effluent gravitates into the ocean outfall system where it diffuses from seabed nozzles at a depth of 80 m. Screenings, grits, and separated scum are dewatered and trucked to offsite landfill. Finally, digested sludge is pumped from the bottom of the digesters, then dewatered by centrifuge into its final form (known as "biosolids") and sold as a soil conditioner.

There are three partly-buried anaerobic digesters of total volume 35,000 m^3 and a digested sludge storage tank of 4,500 m^3 that supplies the biosolids plant. In each digester biogas released from the digesting sludge is collected in a cover that floats on the sludge; sealing the biogas and rising or falling under steady pressure.

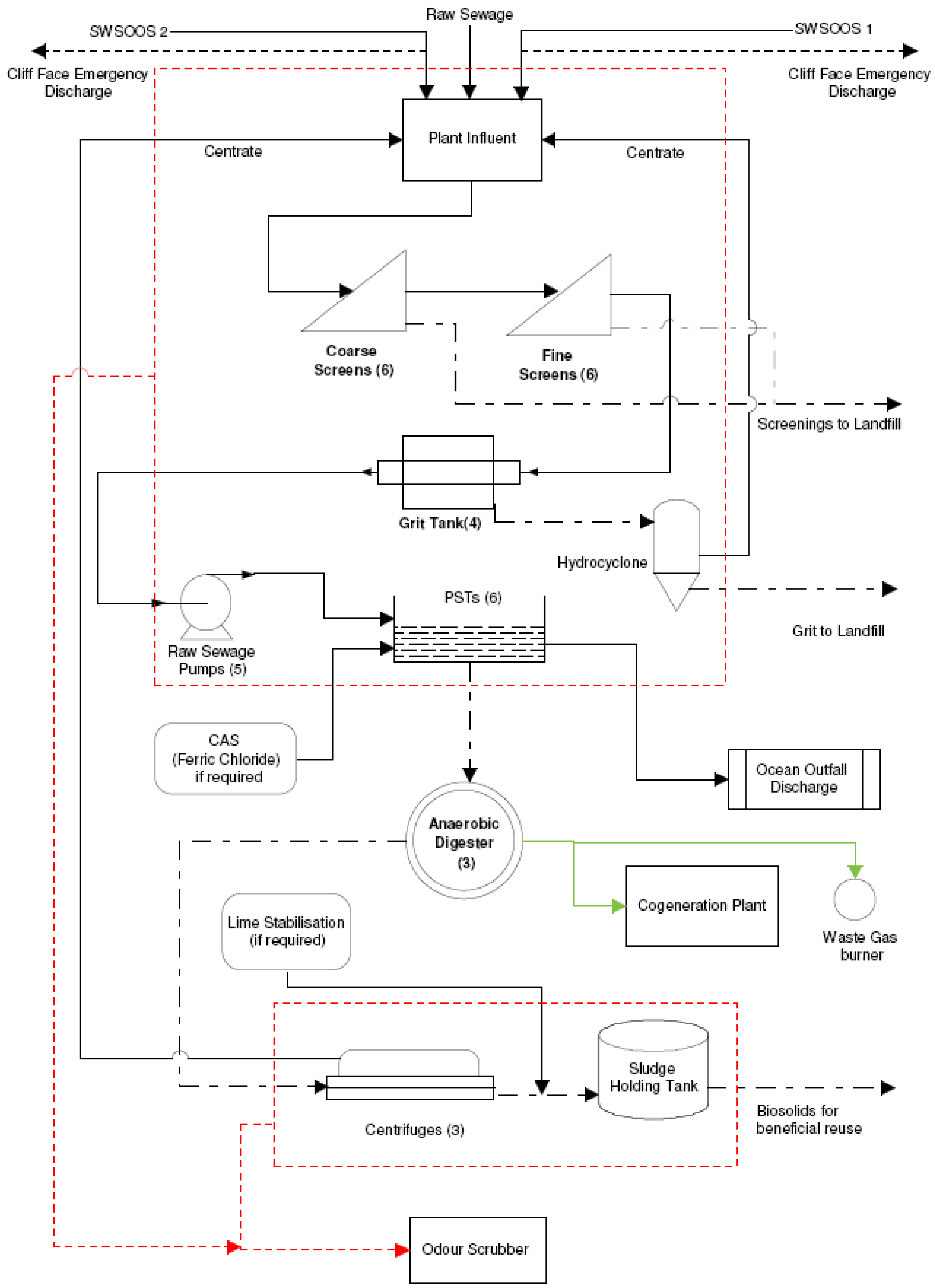


Figure 1.3.1 Malabar STP process flow diagram

Some of the raw biogas is drawn off from the cover, compressed, and re-injected throughout each digester to continuously mix the sludge. Mixing is also done by recirculating the sludge through external heat exchangers that maintain the digester temperature. The heat exchangers are heated either by cooling water from the cogeneration system or by back-up biogas burners.

Some of the recirculated sludge is directed at breaking up the floating scum layer that otherwise hinders biogas release into the digester cover (and also reduces the active volume of the digester). Any biogas excess to the net flow drawn off by the cogeneration system is flared.

Figure 1.3.2 is a photograph of the floating cover of Digester 3 and its biogas pipework. Figure 1.3.3 is a cross-sectional elevation view of Digester 5 showing the internal sludge recirculation pipework, scum-breaking jets, floating cover, and external biogas recirculation pipework. The floating cover is shown in its maximum upper and minimum lower (resting on the internal corbels) positions. The normal range of the digesting sludge surface level is also shown.

Figure 1.3.2 Malabar STP anaerobic Digester 3

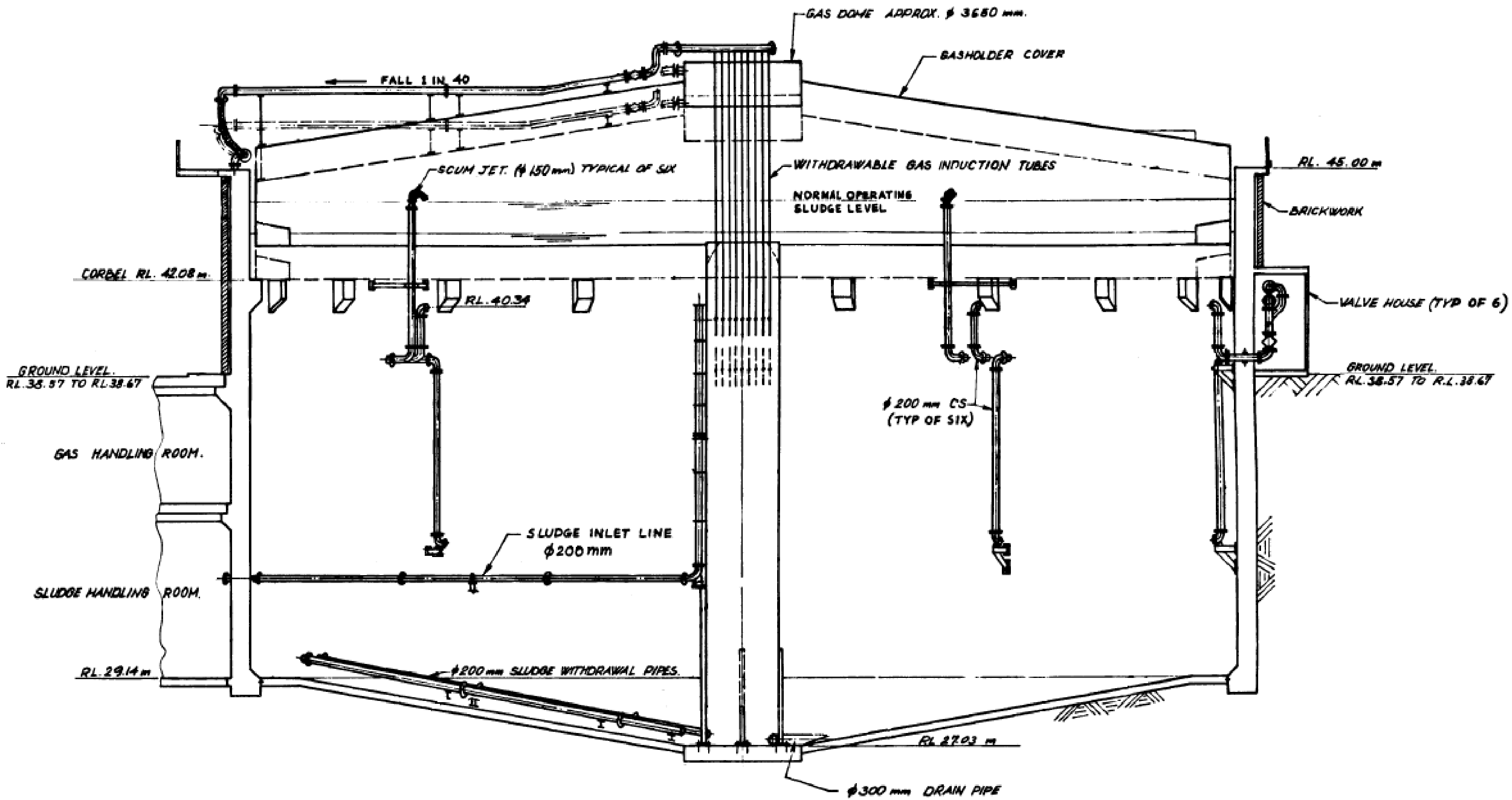


Figure 1.3.3 Malabar STP anaerobic Digester 5 cross-section

The solids retention time (SRT) of the digesters is 15 – 19 days depending on the day-to-day flow rate and solids content of the influent (Sydney Water 2004). Upstream treatment processes, as described above, can also change the solids load entering the digesters.

The primary sludge is fed by continual partial batching into the digester's external heating circuit, where a small volume of fresh sludge (at ambient temperature) is regularly added to offset periodic removal of digested sludge (at the operating temperature of nominally 35 ^{o}C) from the conical base of the digester.

The aim of digester operation is to feed enough fresh sludge to sustain the bacterial colony inside, but to not overload it or cause thermal shock. At the same time the primary sludge feed must balance with the average solids settling rate of newly arrived influent in the sedimentation tanks and with the rate of digested sludge removal from each digester. Finally, the digested sludge must meet licence conditions on organic content and must be removed slowly enough to avoid washing out more of the bacterial colony than can be replaced within the hydraulic retention time (HRT) that is imposed by the digester's active volume and the feed rate of primary sludge.

Any two or all three of the Malabar STP digesters may be operated either in parallel, where the whole digestion process occurs simultaneously in their combined volume, or in series, where staged digestion at different temperatures is possible.

Malabar STP has a chemically-assisted sedimentation (CAS) dosing plant which adds ferric chloride to the influent at the grit separation stage. This polymerises the fine particles of organic solid into aggregates that have higher settling rates, thus tending to increase the mass of sludge recovered in the sedimentation tanks and so available for digester feeding. It is rarely necessary to use CAS in order to meet Malabar STP's license limit on total solids in the effluent.

1.4 Cogeneration system

The cogeneration system at Malabar STP was commissioned in 1999. It consists of three reciprocating engine driven generators having a continuous rated capacity of 975 kW_E each, giving a total capacity of 2,925 kW_E compared with the maximum site electrical load of about 3,600 kW_E. The system supplies around 12.4 GWh_E per annum, or approximately 40% of Malabar STP's annual electricity consumption.

Figure 1.4.1 is a photograph of the cogeneration system engines (inside their acoustic enclosures).

Figure 1.4.1 Malabar STP cogeneration system engines

Figure 1.4.2 is a simplified SCADA output screen showing major components of the cogeneration system.

Raw biogas is drawn from the anaerobic digesters to the cogeneration system by a variable speed, positive displacement blower. Before entering the blower the biogas passes through a water separator, a refrigerated dryer, and a particulate filter. The compressed, dried, and filtered biogas is briefly stored in an anti-surge vessel that absorbs flow and pressure variations, and then reheated if necessary before entering the common fuel manifold where it is individually metered to each engine.

The blower attempts to maintain digester cover pressure between control set points of 2.2 and 2.6 kPag. Below this range the cogeneration system automatically sheds electrical load in order to leave biogas in the digester and so raise the pressure. Above this range the electrical load is increased to capacity to remove biogas and lower the pressure. Sludge level in each digester also varies independently of the rate of biogas removal, and so affects the cover position.

If the flow of biogas exceeds the cogeneration system's firing capacity then the digester sludge heaters (first) and the waste biogas flares (second) are automatically started to dispose of the excess.

Heat removed by the engine's jacket cooling system is transferred to the digester sludge heating circuits, thus making available further biogas for electricity generation by reducing the thermal load on the biogas-fired sludge heaters.

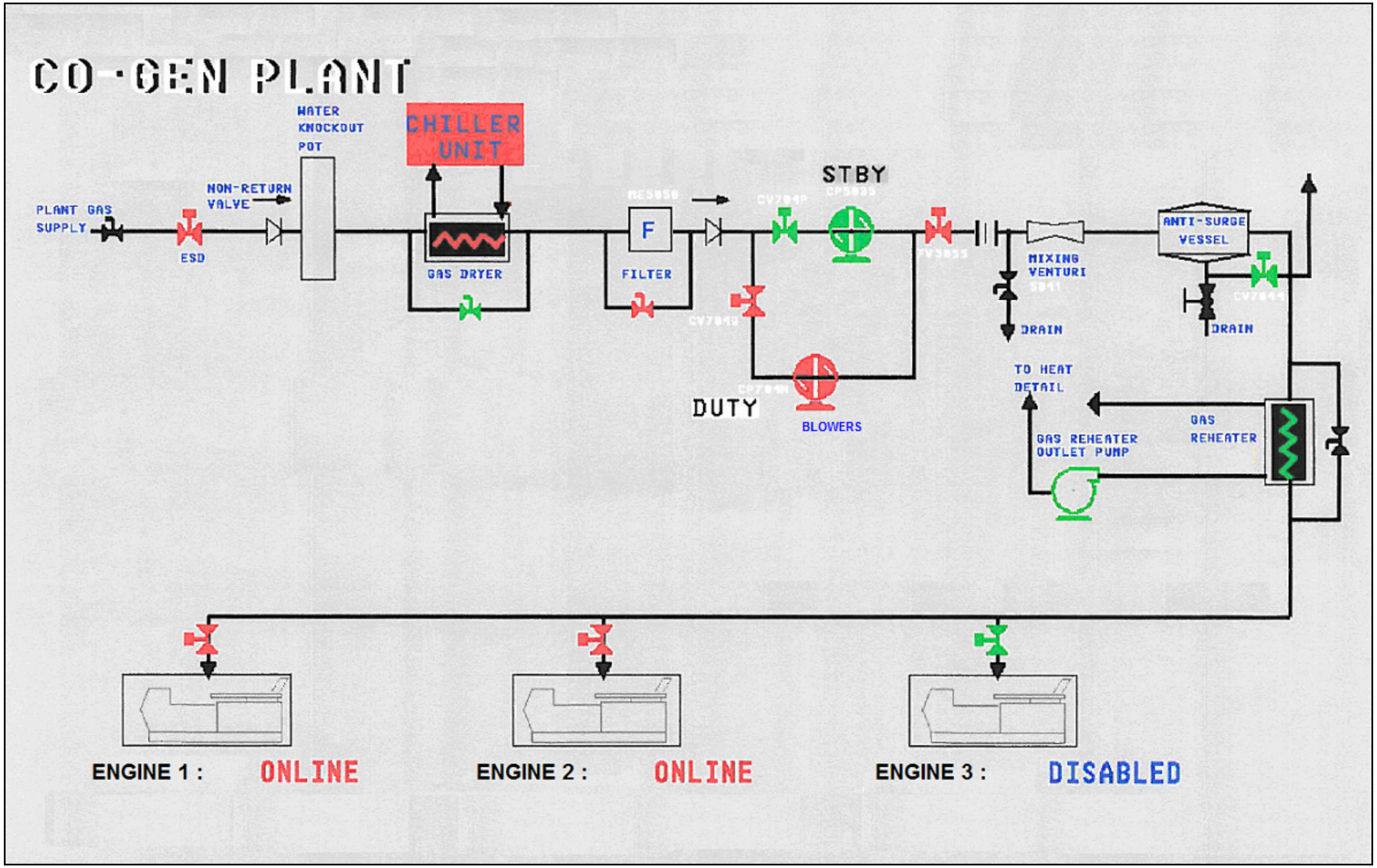


Figure 1.4.2 Malabar STP cogeneration system block diagram

2. Research Questions

The 2,975 kW_E rated cogeneration system rarely generates at a load of more than 2,300 kW_E either for a lack of biogas, low methane content of the biogas, or both. To reflect this situation in monthly performance reporting the system's target load factor is 66%; which is equivalent to a continuous or rolling average load of about 1,900 kW_E over a given period.

The inability to run the cogeneration system at its rated capacity means that up to 1,000 kW_E (based on the target load factor) of additional grid electricity must be imported at a relatively higher unit energy cost in order to maintain treatment operations.

It was initially planned that this research would consider broad questions about the way Malabar STP digesters could be operated so that potentially conflicting time profiles of sludge loading, lagging biogas output, digester heat loading, plant electrical demand, peak energy tariffs (ideally to be avoided by cogeneration of electricity), and digester SRT would be balanced for best overall plant performance.

Due to their complexity answers to such a question were soon found to be beyond the more limited scope of optimising biogas production – considering the time and resources available to complete the project.

The focus of this research then became to identify ways to increase the load factor of the fuel-constrained cogeneration system, or in other words; to consider how Malabar STP could make more biogas, containing more methane, more of the time.

This research was framed by following specific questions about biogas formation within the anaerobic digesters at Malabar STP:

i) What are the most viable means, including plant modifications or use of additional equipment, to achieve higher rates of biogas production within the overall constraints presented by Malabar's primary functions as a sewage treatment plant?

ii) What factors limit the maximum rate of biogas production by AD of a given sewage flow?

iii) What is the maximum sustained rate at which biogas could be produced at Malabar STP?

iv) What factors affect the ratio of methane to carbon dioxide in sewage biogas and how can these factors be optimised at Malabar STP?

v) How does biogas production at Malabar STP compare with benchmark performance data on AD of sewage sludge?

The overall aim of the research was to recommend ways to improve the performance of the Malabar STP cogeneration system by answering these five questions.

3. Literature Review

3.1 Anaerobic digestion

Anaerobic digestion is the process by which complex biodegradable organic matter is broken down by groups of co-dependent bacteria in the absence of free oxygen. It occurs in natural ecosystems and has been used for centuries to stabilise and concentrate organic wastes from human civilisation. AD is particularly well-suited to waterborne wastes such as sewage and animal manures due to the ease with which bacterial colonies can transport and expand within a mixed fluid medium, and the simplicity of systems for storage and transfer of fluid wastes.

AD has seen a revival of interest in recent decades in response to environmental threats from large and increasing volumes of sewage (Ahring 2003, Weiland 2010) and the simultaneous need to reduce the cost of its treatment. The concern of water utilities has historically been to stabilise the solids content in the waste water stream and to safely flare AD biogas – which until recently was considered to be a nuisance by-product. Other benefits of AD such as the potential for biogas power generation and the lower lifecycle cost of AD digesters (compared with aerobic or activated types) have received much less attention in the past.

The anaerobic stabilisation of sewage sludge has the following objectives (Sydney Water 2007):

i) Reduction in pathogens.
ii) Inhibition / reduction in the potential for sludge putrification.
iii) Elimination of offensive odours.
iv) Reduced mass of organic solids for disposal.
v) Energy recovery by the production and utilisation of methane.

In spite of its ancient use and widespread application, the detailed microbiology of AD is still to be fully understood due to the difficulty of using traditional culturing methods to isolate particular anaerobic bacteria and identify their role in active colonies. These gaps in knowledge sometimes result in inexplicable digester failures today, even after long periods of stable operation (Weiland 2010). In the last 20 years molecular and biochemical techniques have been developed (Kuang 2002) that have greatly improved characterisation of microbial communities and the scope for their optimisation in anaerobic digesters.

3.2 Microbiology of anaerobic digestion

AD is most reactive in two temperature ranges; mesophilic AD occurs between 32 – 38 °C with the optimal temperature being around 35 °C, while thermophilic AD occurs in the range 60 – 75 °C. In both mesophilic and thermophilic AD three stages of decomposition may be distinguished: hydrolysis, acidification, and methanogenesis. Some researchers include as a fourth stage the process of acetogenesis – an alternate but parallel route by which up to 70% of substrates from the acidification stage may be converted to methane (Kuang 2002, O'Flaherty *et al.* 2006). A simplified description of what is known about the four stages is given below (Kuang 2002, Deublein and Steinhauser 2008). Figure 3.2.1 is a diagram of the overall process.

It is important to note that all stages of anaerobic digestion must proceed at the same time, but that each stage has a different range of kinetic constants (Gavala *et al.* 2003).

Discussion here is concerned with mesophilic AD as used at Malabar STP. It is noted in passing that thermophilic AD digests more organic solids in less time and has a greater yield of biogas per unit mass of solids, but has higher energy demand for process heating, larger capital and operating cost, and complex process control.

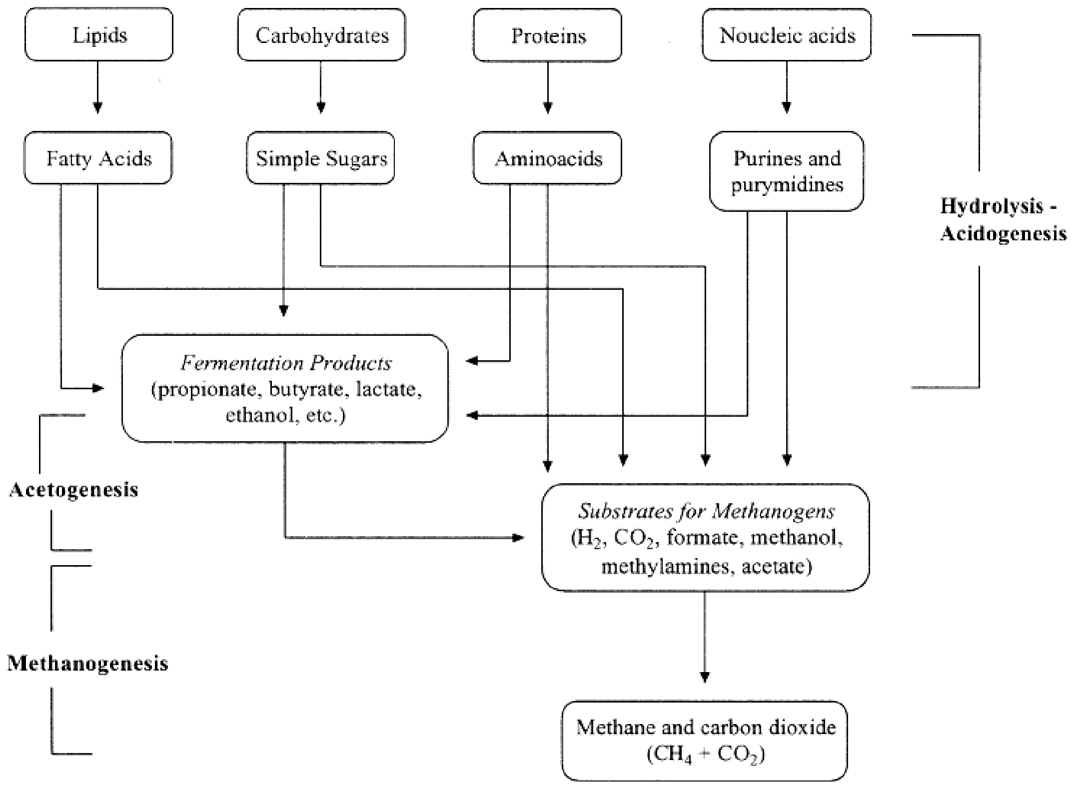


Figure 3.2.1 Stages of anaerobic digestion
(Source: Gavala *et al.* 2003)

3.2.1 Hydrolysis

In this initial stage the organic matter consisting of cellulose, proteins, and long-chain fats, carbohydrates and lipids are cracked into simple monomers by reactions between water and the enzymes excreted by fermenting bacteria. Carbohydrates and fats are hydrolysed within hours, proteins and lipids within several days, and cellulose at a very much slower rate – if at all. It is noted that the success of this stage depends on such variables as particle size, mixture pH, enzyme production, diffusion and adsorption rates within the host medium, and bulk motion of the particles (Gavala *et al.* 2003).

3.2.2 Acidification

In the second stage the monomers formed during hydrolysis are converted to short chain, organic volatile fatty acids (VFA including butyric, proprionic, and acetic acids), acetate, alcohols, hydrogen, and carbon dioxide. The concentration of hydrogen ions formed during this stage influences the simultaneous production of acetate: the higher the partial pressure of hydrogen in the bacterial colony, the less acetate is produced. The effect of hydrogen partial pressure is also understood to be critical in determining the route of interdependent methane formation taken during the final methanogenesis stage and in maintaining the overall thermodynamic viability of the digestion process (Kovács *et al.* 2005, Deublein and Steinhauser 2008). Factors affecting the hydrogen ion concentration during acidification are not yet clear (Demirel and Scherer 2008). Acidifying bacteria are known to metabolise rapidly, typically reproducing within 4 – 12 hours and requiring a retention time of 6 days or less (Sydney Water 2007).

3.2.3 Acetogenesis

A portion of the products of the acidification stage may be further oxidised to acetate, hydrogen, and carbon dioxide by bacteria known as obligate hydrogen producing acetogens (OHPA). The metabolism of OHPA is only viable when the partial pressure of hydrogen in the colony is lowered by the simultaneous growth of hydrogen-utilising methanogens, sulphate-reducing bacteria (SRB) which compete with them, or homoacetogens; all of which consume hydrogen produced by the acetogens (O'Flaherty *et al.* 2006).

Problems with stable methane production from operating digesters tend to arise during acetogenesis, when faster-growing and less sensitive microbes, in particular SRB which are present in all digesters, may get the upper hand - leading to reduced pH, the formation of odorous hydrogen sulphide rather than methane, and ultimate collapse of the anaerobic colony.

3.2.4 Methanogenesis

The final stage sees conversion of remaining substrates to methane and carbon dioxide, plus traces of hydrogen sulphide, nitrous oxide, and other gases. There are two groups of methanogenic bacteria (O'Flaherty *et al.* 2006). The first are hydrogenophillic or hydrogenotrophic species which form methane by the reduction of hydrogen and carbon dioxide. The second are acetoclastic or acetotrophic species, which generate methane by acetate decarboxylation. The share of methane generated by each species is determined by the exact reaction path of the substrate through the previous three stages and on the success of interspecies hydrogen transfer during acetogenesis. Stable methanogenesis requires between 4 – 10 days for the bacteria to reproduce and between 12 – 35 days for digestion to complete.

At a molecular scale, the fraction of methane produced in this final stage is currently thought to be determined by the concentration of hydrogen ions available for interspecies transfer (Bagi *et al.* 2007). The final composition of sewage biogas has a typical methane fraction of between 50 – 70 %vol. Other components and their effect on biogas properties are as listed in Table 3.2.1.

Table 3.2.1 Biogas components

Component	*Content*	*Effect*
CO_2	25–50% by vol.	– Lowers the calorific value – Increases the methane number and the anti-knock properties of engines – Causes corrosion (low concentrated carbon acid). if the gas is wet – Damages alkali fuel cells
H_2S	0–0.5% by vol.	– Corrosive effect in equipment and piping systems (stress corrosion); many manufacturers of engines therefore set an upper limit of 0.05 by vol.%; – SO_2 emissions after burners or H_2S emissions with imperfect combustion – upper limit 0.1 by vol.% – Spoils catalysts
NH_3	0–0.05% by vol.	– NO_x emissions after burners damage fuel cells – Increases the anti-knock properties of engines
Water vapour	1–5% by vol.	– Causes corrosion of equipment and piping systems – Condensates damage instruments and plants – Risk of freezing of piping systems and nozzles
Dust	>5 μm	– Blocks nozzles and fuel cells
N_2	0–5% by vol.	– Lowers the calorific value – Increases the anti-knock properties of engines
Siloxanes	0–50 $mg\,m^{-3}$	· Act like an abrasive and damages engines

(Source: Deublein and Steinhauser 2008)

3.2.5 Inhibiting and rate limiting factors

Methanogenesis is generally considered to be the foremost rate limiting stage in AD owing to the inherently slow growth rate of methanogenic bacteria, even under ideal conditions. Methanogens are also highly sensitive to rapid changes in process conditions, namely; organic loading rate, digested sludge removal rate, solids particulate size distribution, exposure to light, digester temperature, and pH. Intermediate AD products such as volatile fatty acids, hydrogen sulphide, ammonia, any chlorinated hydrocarbons, and heavy metals (above certain minimum and necessary concentrations) are all known to be toxic to methanogenic bacteria (Gavala *et al.* 2003). In addition some of the organic substrates in primary sludge that are consumed by AD can themselves be inhibitory at high concentration.

Some researchers claim that hydrolysis is the ultimate limiting step because it "is limited by the restricted accessibility of the extracellular enzymes produced by the hydrolysing bacteria to the intracellular polymeric materials which are protected by cell membranes" (Cui and Jahng 2006, p531).

3.3 Design of sewage sludge digesters

Malabar STP digesters are of the single-stage, high rate design that is most common in modern centralised mesophilic AD systems. In this design all four stages of AD are made to occur in the same enclosed volume of sludge. Development of this design and its variants began in the 1960s based on earlier anaerobic methods such as open lagoons and septic tanks (Haandel *et al.* 2006). Advances in the design reflected better awareness of AD as a process, and included vigorous sludge mixing to improve exchange between bacterial species, separation of the primary sludge inlet and the digested sludge outlet in order to increase and even out SRT, improved sludge feed rate control, and external sludge heating to maintain mesophilic conditions in the digester.

The major alternative to this design in anaerobic systems is the multi-stage, high rate digestion process train that has been found suitable for both mesophilic and (more often) thermophilic AD, especially when the influent has unusually high chemical oxygen demand (COD) (Haandel *et al.* 2006). In this design the initial hydrolysis and secondary acidification stages occur separately in a single tank, sometimes in the thermophilic AD temperature range in order to increase the rate of these reactions. The partially digested sludge is then transferred into a second and, sometimes, third tank for the acetogenesis and methanogenesis stages. Difficulties arise in limiting SRT to prevent methane formation in the first tank, and in judging the point at which the contents of the first tank should be transferred out to begin acetogenesis.

The process and mechanical design of high rate digesters is normally based on a combination of hydraulic retention time (HRT) and either COD (Batstone 2006) or volatile solids (VS) loading using empirical data from previous designs. A number of researchers observe that this practice has led to digesters that are "mostly operated as black boxes, taking the effluent concentration as an output value that cannot be improved… the [digester] control strategy [does] not generally take into account processes occurring at the microorganism level" (O'Flaherty *et al.* 2006, p39). Anaerobic digesters are easily imbalanced causing terminal increases in the concentration of organic acids (Stamatelatou *et al.* 1997). As noted earlier, modern techniques for characterising anaerobic communities permit more accurate modelling of AD (Kuang 2006, O'Flaherty *et al.* 2006) and should ultimately lead to more precise plant design and operation.

3.4 Estimating biogas methane yield

The volumetric biogas yield and energy content (i.e. methane fraction) from sewage sludge AD is normally estimated by empirical methods. These methods are based on measurement of actual COD or VS in the influent and on some knowledge of the volume of biogas historically produced per unit mass of COD or VS reduction occurring either within that digester or others of a similar design. Biogas yield at new plants is normally inferred from similar existing installations rather than calculated explicitly. Using this method always assumes a range of methane fraction; unless it too is inferred from past measurements. From the discussion of AD stability in Section 3.2 it may be appreciated that empirical estimates of sewage biogas yield can be wildly inaccurate.

Table 3.4.1 shows benchmark ranges for certain parameters that are characteristic of stable operation in single-stage mesophilic sewage digesters.

Table 3.4.1 Characteristics of stable mesophilic AD in single-stage sewage digesters

Parameter	Units	Range
Sludge temperature	^{o}C	32 – 38
Sludge temperature change	$^{o}C/d$	≤ 0.5
Biogas yield	m^3/kg_{VS}	0.75 – 1.10
Methane yield	m^3/kg_{VS}	0.35 – 0.60
pH	-	6.8 – 7.2
Alkalinity	Mg/L	2000 – 5000
VFA	Mg/L	25 – 200
VFA / Alkalinity ratio	-	0.01 – 0.05
VSLR	$kg_{VS}/m^3/d$	1.6 – 4.8
Influent solids concentration	%wt	5 – 6
VS fraction of influent solids	%	60 – 85
VS reduction	%wt	50 – 60

(Sources: Sydney Water 2007, Taricska *et al.* 2007, Deublein and Steinhauser 2008)

Mathematical modelling of AD has advanced during the last 20 years (Batstone 2006, Gerber and Span 2008) into generalised, dynamic, high order non-linear, physicochemical models that consider substrate chemistry, mass transfer, fluid motion, and reaction thermodynamics of each AD stage, and which do not necessarily need to be validated on a particular digester. In 2001 a project team of the International Water Association published an authoritative computational routine known as Anaerobic Digestion Model No. 1 (International Water Association 2010). The objective in developing such models has been to better understand and improve the performance of AD for any given organic substrate, particularly at the design stage of new industrial digesters. Modelling has gained fresh impetus during the last 5 – 10 years with wider appreciation of the low cost and potential energy yield of AD.

These elaborate models are noted here for future reference. Their application in forecasting effects on Malabar STP biogas yield and methane content of the optimising techniques reviewed in Section 3.5 is beyond the scope of this research.

Instead, a simplified steady-state model developed for AD of slurried pig manure (Chen 1983) and adapted to sewage sludge was used to estimate a theoretical maximum biogas flow rate at Malabar STP (refer Section 4.4.3).

SW has previously licensed the STOAT and BioWin dynamic simulation software for modelling and diagnosis of treatment processes. But the cost and heavy data requirements of the verification process for this software inhibited their use by operators and designers alike, and SW ceased renewing its licenses in 1999 (Sydney Water 2009a).

3.5 Techniques to increase biogas volume and methane yield

This section reviews published research on a range of methods for increasing both the overall volume of biogas generated by sewage sludge AD and the methane content of the biogas. Methods tend to fall into three categories:

i) Pre-treatment of primary sludge.
ii) Modifying the composition of primary sludge.
iii) Improved control of digestion processes.

The potential increases in volume and methane content that could be expected from each technique is stated. This together with some practical considerations forms a basis to compare of the viability of these techniques at Malabar STP.

3.5.1 Comments on CH_4/CO_2 ratio

Before discussing ways to optimise methane content it is appropriate to consider why sewage biogas from AD is not 100 %vol methane. This research found it well established in the literature that the total redox potential of the AD colony controls the CH_4/CO_2 ratio (Pind *et al.* 2003). During methanogenesis the reduction of carbon by hydrogen to yield methane (preferred for power generation), rather than the oxidation of carbon to yield carbon dioxide, relies on the availability of hydrogen. Ultimately, the different kinetic rates of simultaneous AD stages always dictate that limited hydrogen is available for the reduction reaction.

Digester pH and alkalinity control the evaporation of carbon dioxide and so affect the CH_4/CO_2 ratio of biogas leaving a digester, but only in that more or less of the carbon dioxide that is actually produced remains dissolved.

The CH_4/CO_2 ratio of biogas may be increased by allowing more time for digestion (longer SRT), by the presence of long chain hydrocarbons rich in fats (up to a limit at which these begin to interfere with pumping and mixing), and by increasing the digester pressure and liquid content (Deublein and Steinhauser 2008). Increased digester pressure and liquid content both result in a higher concentration of dissolved carbon dioxide removed with the liquid digestate. However, pressure increases in an existing digester generally lead to loss of biogas through increased cover seal leakage, and greater liquid content has the negating effect of reduced solids content available for digestion.

3.5.2 Thermal pre-treatment and solar-assisted heating

Thermal pre-treatment or hydrolysis of primary sludge is one of numerous pre-digestion processes that aim to rupture the cell membranes of long-chain polymer molecules; releasing the more easily digested organic material contained inside. This increases the rate of VS break down by AD; reducing the mass of residual sludge, and converting more of the VS to biogas. In thermal hydrolysis the primary sludge is artificially heated under pressure and “soaked” before it is fed to the digester. Soaking temperatures in the range 160 – 180 ^{o}C at pressures of 500 – 700 kPag are common for soaking periods of 30 – 60 minutes. Thermal pre-treatment may be applied to all or part of the sludge flow.

The method is the basis of several commercial technologies, the best known of which are the proprietary CAMBI and BioThelys processes (Water Environment Research Foundation 2008) that are applied to the whole sludge flow. Both have been implemented at existing European STPs and both have resulted in significant increases in the volume of AD biogas (in the order of 50%). Both have the disadvantages of significantly increased process complexity and energy consumption, and the requirement to dewater primary sludge before it is heated. Both are claimed by their proprietors to produce a net energy gain when the increased biogas production is accounted for – a claim that is disputed by some researchers (Ahring 2003).

Process heating of sewage sludge using solar concentrators has been considered as a way to reduce the quantity of biogas that is drawn off and used to maintain digester temperature. During the 1980s the United States Environmental Protection Agency made a detailed analysis of solar heating primary sludge anaerobic digesters at STPs of capacity 37.8 ML/d using flat-plate collectors in nine US cities (USEPA 1982). The present worth of conserved biogas was compared to the present worth of the solar energy collection system. This study found that solar heating was uneconomical at any scale over any period at any location. In then-current dollars the unitised heating system cost was approximately three times that necessary to make the system worthwhile (USEPA 1982).

In more recent work Axaopoulos *et al.* built an experimental solar heated anaerobic digester of 45 m^3 active volume, successfully operated it at a relatively highly insolated location (in Greece), and with the results validated a TRNSYS simulation of its performance on pig manure with SRT of 6 days. The four 8 m^2 solar collectors were built into the digester roof and circulated warmed water by thermosiphon effect through a coil heat exchanger fixed within the sludge volume.

The study concluded that methane production strongly influenced the economic viability of solar assisted heating, but that methane production itself “heavily depends on proper management of the chemical and physical environment within the digester” (Axaopoulos *et al.* 2001, p163). The solar heating merely offset biogas use: it had no effect on biogas production *per se* and the AD bacteria fared neither better nor worse for it.

Low thermal yields (relative to the heat load of industrial-scale digesters), except in a limited number of specific locations, and the need to maintain back-up heating for night operation, have generally continued to hinder widespread use of solar energy for this purpose, particularly at large urban STPs with space restrictions.

3.5.3 Ultrasonic pre-treatment

When passed through primary sludge ultrasonic sound waves cause cavitation in which microscopic bubbles of vapour form under negative pressure and then collapse almost immediately. The resulting shock pressure (10,000 – 20,000 kPag) and point temperature rise (1000 – 2000 °C) lead to the destruction of bacterial cell membranes, with the typical result of halving the minimum SRT, increasing biogas volume by up to 40%, and reducing the mass of digested sludge by 40% (Deublein and Steinhauser 2008). There is no effect on methane fraction.

Ultrasonic frequencies of 40 kHz have been found to be most effective, and are typically applied to a bypass flow of around 30% of the total volume of primary sludge entering an anaerobic digester. Exposure times of up to 100 s may be necessary. Proprietary ultrasonic pre-treatment technology is available and, as with thermal pre-treatment, a net energy gain is claimed due to increased volume of biogas offsetting the additional electricity required for the ultrasound generator(s).

3.5.4 Microwave pre-treatment

Microwave irradiation is a relatively recent approach to thermal degradation of primary sludge that improves on slower indirect heating methods. Whether microwaves *per se* have some additional sterilising effect is still debated. Laboratory scale investigations of microwave treatment have found that it effectively disrupts sludge bacterial cell membranes and so releases more intracellular material for shorter hydrolysis and increased biogas volume.

Figure 3.5.1 shows the effects on cumulative AD biogas production of 2,540 MHz microwave irradiation on a batch sample of mixed primary and thickened sewage sludge at temperatures between 120 – 170 °C and exposure times of either 5 or 10 minutes (Qiao *et al.* 2010, p148). The results suggest that an increase in biogas volume of up to 25% is possible upon AD of the irradiated sludge over a 15 day SRT.

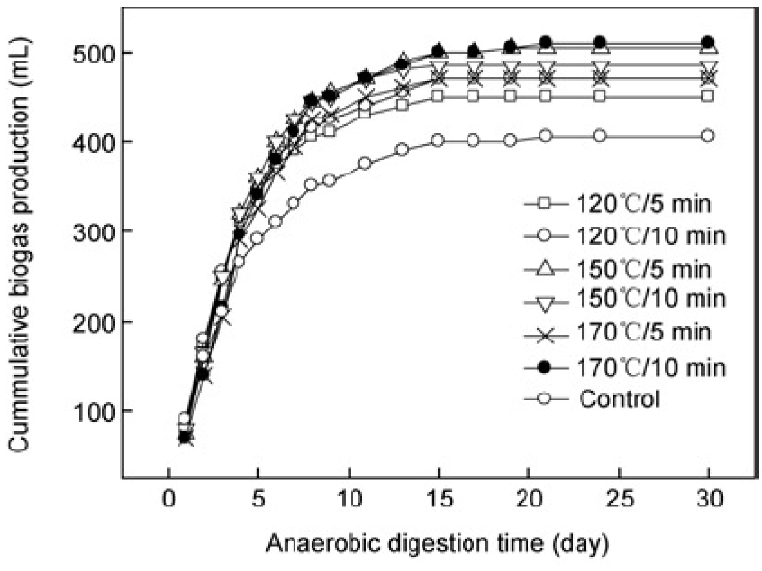


Figure 3.5.1 Effect of microwave irradiation on AD biogas volume
(Source: Qiao *et al.* 2010)

3.5.5 γ-Ray pre-treatment

Laboratory-scale small batch experiments have shown that γ-irradiated primary sludge has reduced particle size distribution, increased levels of soluble COD substrates, and increased production of biogas during AD compared to non-irradiated sludge in direct proportion to the dose strength (Yuan *et al.* 2008). Sludge disintegration occurs very quickly under γ-irradiation (<1 s), but total irradiation time in reported experiments has been in the order of hours for small sample volumes of sludge (<5 L). It could be speculated this was due to low intensity of the particular radioelement source of the γ-irradiation. Figure 3.5.2 shows results from one set of experiments (Yuan *et al.* 2008) which suggest increases in biogas volume of up to 35% are possible during subsequent AD of γ-irradiated sludge compared to non-irradiated sludge at SRT of 15 days beginning with solids content of just 1.5 %wt.

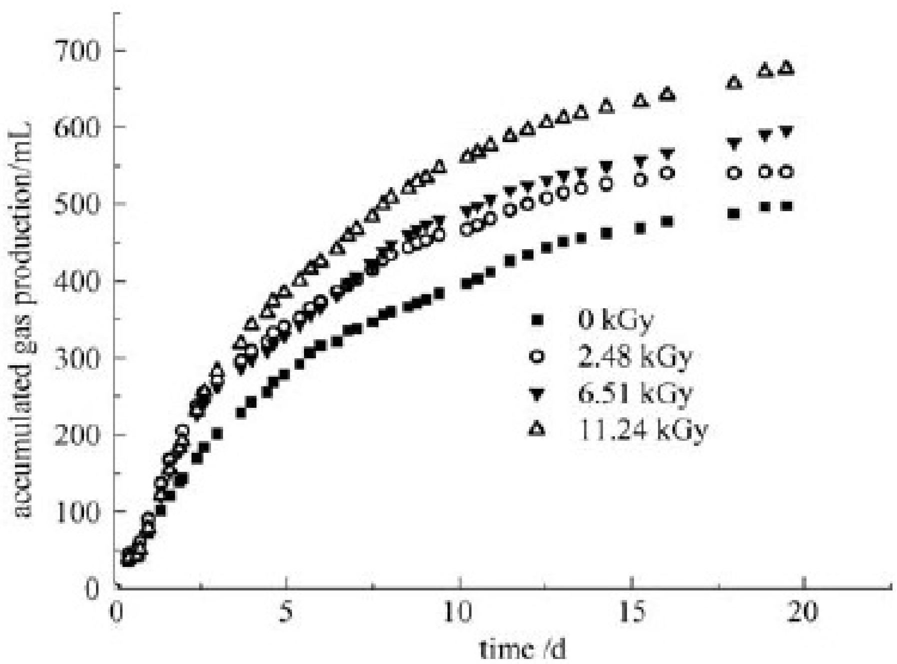


Figure 3.5.2 Effect of γ-irradiation on AD biogas volume
(Source: Yuan *et al.* 2008)

3.5.6 Electron beam pre-treatment

Electron beam irradiation of waste water is known to form reactive chemical species in solution that aid the conversion of pollutants through redox reactions, precipitation, and organic decomposition (Shin and Kang 2003). It has been applied to a variety of water disinfection and water-borne solids reduction problems. Laboratory scale research has also shown that electron beam irradiation increases soluble COD (particularly by dramatic increases in soluble proteins and carbohydrates) available for subsequent AD. In one such experiment on thickened sludge in the range 2.4 – 3.2 %wt solids, between 189% and 287% of additional biogas was produced by AD over the same hydraulic retention time as the control sample, owing to the "large quantity of soluble organic materials leached out by the electron beam radiation" (Shin and Kang 2003, p236).

3.5.7 Substrate improvement

The aim of pre-treatment methods discussed above is to increase the availability of readily digestible organic substrates within sewage sludge for AD bacteria. This section considers what substances may be mixed with primary sewage sludge with the same aim, giving either or both increased biogas volume and methane fraction.

Various organic wastes have been mixed with sewage sludge to improve the rate of hydrolysis and the availability of hydrolysis products for subsequent acidification or acetogenesis of both the sewage sludge and the added substrate. Any biomass material can be used for co-digestion provided it contains carbohydrates, proteins, fats, cellulose, and hemi-cellulose as the main components (Deublein and Steinhauser 2008). Materials include macerated restaurant (food) scraps, shredded grass clippings, pulverised urban greenwaste (wood), abattoir wastes (subject to local regulations), and sugar refining wastes. The higher the total COD of the mixed materials, the greater is the potential for biogas formation. Wastes for co-digestion should ideally have a similar (or smaller) particle size distribution to the primary sludge or else be in liquid form (Ahring 2003).

The largest European AD plants all co-digest feedlot animal manures that are mixed with other organic wastes which have higher biogas potential, in particular food scraps and fatty wastes such as grease trappings (Ahring 2003). It is known that dramatic increases in biogas volume can result from co-digestion, provided there is sufficient excess digester active volume for the minimum SRT necessary on the combined influent.

As an example, addition of 5 %vol (or 50 L) of fish oil to 1 m^3 of fresh cattle manure has led to increases in the order of 200 %vol in AD biogas (Ahring 2003) compared to that from untreated manure. It is not reported what effect if any the oil had on the stabilisation of the manure, the quantity of residual sludge, or its chemical and handling properties. No change in methane content was reported either.

More recent research in the US reported increases of between 10 – 40% in AD biogas volume due to co-digestion of food wastes with sewage sludge (California Energy Commission 2008). Figure 3.5.3 shows the effect in laboratory batch tests of three types of food processing wastes in 50 %wt mixtures with sewage sludge on biogas volume during subsequent mesophilic AD over a 20 day SRT. The control was 100 %wt sludge.

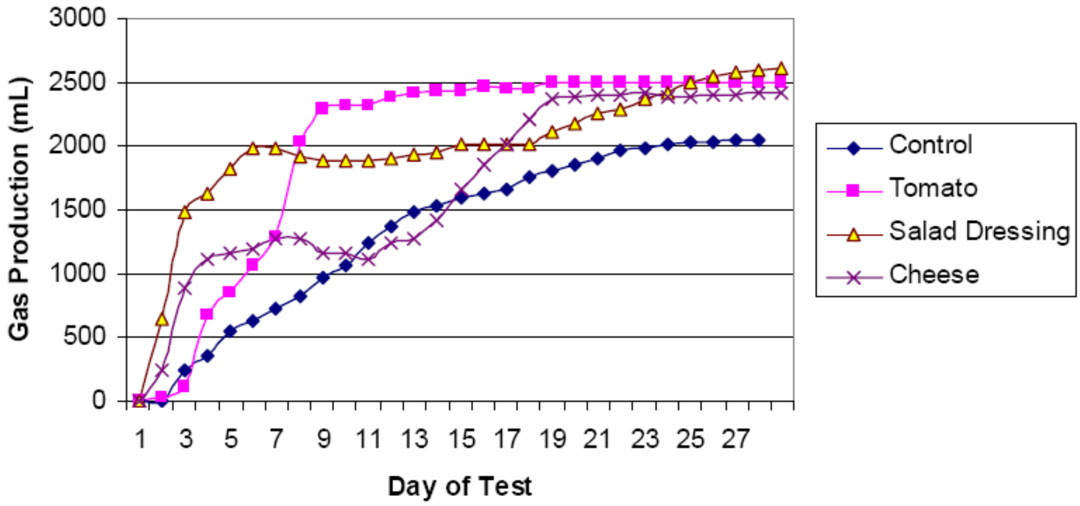


Figure 3.5.3 Effect of co-digested food processing wastes on AD biogas volume
(Source: California Energy Commission 2008)

Results from these laboratory scale tests guided pilot-scale trials on an industrial continuously fed digester, and became the basis of an empirical model to predict co-digestion biogas production. The pilot-scale test showed an increase of at least 12 %vol of biogas from sludge co-digested with 10 %wt food waste sustained over a test period of some 7 months. Net VS destruction in the digester also increased in a similar ratio. The researchers noted that large spikes in biogas production following bulk digester feeding with pure food wastes caused havoc with the existing biogas handling/flaring system, and they recommended instead that food wastes be continuously blended with influent sludge.

3.5.8 Sludge thickening

This section considers methods of sludge “thickening”, by which the solids content of wet sludge fed to AD digesters is increased above what can be achieved with primary sedimentation alone. As with other methods discussed above, the intended result is a higher concentration of organic substrate that can support larger bacterial colonies which produce more biogas, but that stays within the maximum SRT on a given digester. Chemical and gravitational methods only are discussed here, as they are the most suitable for primary sewage treatment.

Thickening sludge by dosing the raw influent with ferric chloride has been trialled at a number of SW primary treatment plants, where it has been demonstrated to increase the volume of AD biogas by increasing settled solids concentration in the primary sludge. Increases of up to 30 %vol of biogas produced per day over untreated sludge have been recorded with all else the same. Malabar STP is equipped with a permanent ferric chloride dosing (or CAS) system as described in Section 1.3. In this mode of operation about 10mg/L of ferric chloride solution and 0.5mg/L polyelectrolyte are added to improve solids capture. At this dose rate, approximately 55 %wt to 60 %wt of suspended solids are removed, compared to about 50 %wt when CAS is not used. As noted earlier, Malabar STP normally meets its license limit on total solids discharge without using the CAS system.

Sydney Water investigations have found that "while higher doses of chemical would result in greater removal of solids, sludge quantities generated at the dose of 10mg/L ferric chloride are at the limit of the sludge treatment system's capacity" (Sydney Water 2004, p27). CAS is currently not a viable means for increasing biogas volumes at Malabar STP and it appears that any technique of increasing the solids content for more biogas production would have a practical limit at Malabar STP of 10 %wt additional solids capture – with the downstream plant in its existing configuration.

Gravitational sludge thickening is by the same process to that occurring in primary sedimentation; the influent flow rate is slowed so that the solid particles sink and collect at the bottom. Thickeners are typically cylindrical tanks (diameter < 50 m) with conical bases; the thickened sludge is pumped out from the lowest point at the apex of the cone while the overflow is returned upstream to the primary sedimentation system. Primary sludge thickened in this way typically has a practical upper limit of 5 – 10 %wt solids (Sydney Water 2009b) before thickeners become too large to be built and operated economically.

Centrifuge and belt press thickening of sludge are alternatives to gravitational methods that offer similar increases in solids fraction, with reduced space and installation costs, but with higher operating costs.

3.5.9 Digester mixing regime

The digester mixing regime either impedes or promotes growth of the AD bacterial colony. Mixing promotes growth by supplying stage organisms with fresh substrate, maintaining a stable temperature throughout the digester, moving the products of metabolism to receiver organisms, separating biogas from the liquid phase and moving it out of the digester, breaking up floating or submerged layers of sludge and scum, and preventing undigested solids from entraining with the discharge sludge. At the same time, excessive mixing can impede growth and biogas production by disrupting interspecies hydrogen transfer or by simply killing the shear-sensitive bacteria (Deublein and Steinhauser 2008).

It is commonly observed that gas-mixed sludge digesters produce a surge in biogas flow rate immediately after starting a mixing cycle, even though the digester's liquid contents are continuously turned over through the sludge heaters. Continuous mechanically-stirred digesters do not show this tendency. In general a continuous, careful, but intensive mixing action should be used (Deublein and Steinhauser 2008).

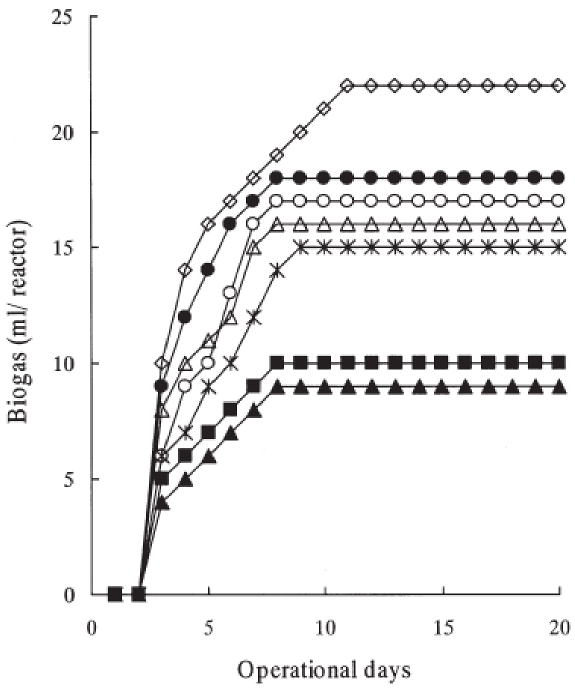
It is noted that prompt removal of biogas from the digester has a major effect on increasing the reproduction of microorganisms in anaerobic digesters. Also, mixing with compressed biogas is known to inhibit the formation of hydrogen sulphide (H_2S) (Deublein and Steinhauser 2008), albeit at the expense of having that portion of the total biogas produced available for energy recovery.

Mechanical scaling effects in trying to reproduce results from laboratory apparatus on real, full-sized industrial AD digesters hampers improved mixing, although advances in computational fluid dynamics (Latha *et al.* 2009) continue to improve predictions of what will happen.

3.5.10 Partial inoculation with aerobic thermophilic sludge

Thermophilic AD occurs in the temperature range 60 – 75 °C and, in any direct comparison, normally has a higher gross biogas yield than mesophilic AD. Researchers have found that small quantities of seed sludge taken from aerobic thermophilic (AT) digestion processes and added to the influent of a mesophilic anaerobic digester will also increase biogas yields from the latter.

In one case it was found that the addition of 5 %vol AT sludge (having 1.2 %wt of volatile solids) to primary sludge improved the production of biogas in a separate mesophilic AD process (Miah *et al.* 2005). Biogas production within the mesophilic process *decreased* as the seed volume of AT sludge was increased further (e.g. to 7 %vol and 10 %vol). The optimum additional volume and the pre-treatment temperature of the AT sludge for maximum biogas production was 5 %vol and 65 °C, at which the biogas volume increased by some 150% over that from unseeded sludge during subsequent AD having SRT of 15 days. Figure 3.5.4 shows the results of these experiments.



symbol	%wt AT sludge
▲	0
△	1
●	3
◊	5
○	7
ж	10
■	20

Figure 3.5.4 Effect of aerobic thermophilic sludge seeding on AD biogas volume
(Source: Miah *et al.* 2005)

3.6 Summary of effects of optimising techniques

Table 3.6.1 summarises the techniques reviewed above. It shows their maximum potential effect on the biogas volume and methane fraction generated from a unit mass of sewage sludge. Advantages and disadvantages of each technique at Malabar STP that were discerned during this research are stated together with the source of the information. The purpose of this table is to enable discussion and to guide selection of the most viable techniques for Malabar STP (refer Section 6).

Table 3.6.1 (A) Effect of optimising techniques on sewage AD biogas volume and methane fraction

Technique	Δ% biogas volume	Δ% biogas CH_4 fraction	Benefits at Malabar STP	Concerns at Malabar STP	Source(s)
Pre-treatment					
Thermal hydrolysis	0 to 400%	negligible	• Significant increase in biogas m^3/kg_{VS} • Significant net energy gain • Reduced mass of biosolids	• Relatively high cost • Process complexity • Suited to new AD plant, rather than retrofit	Pérez-Elvira *et al.* 2006
Ultrasonic	0 to 40%	negligible	• Relatively low upfront cost • Simple operation, external to sludge circuit • Net energy gain • Commercialised technology • Suited to retrofit • Part influent flow can be treated • Reduced mass of biosolids	• Potential cavitation in sludge handling plant • Potential vibration in sludge handling plant • Unknown reliability of equipment in comparison with other STP components	BiogasMax 2010, Deublein and Steinhauser 2008, Sydney Water 2009b
Microwave	0 to 25%	negligible	• Rapid sludge disintegration • Simple operation, external to sludge circuit • Suited to retrofit	• Laboratory scale demonstrated only • Net energy gain unproven at full scale • Suitability in continuous process	Qiao *et al.* 2010
Electron beam	0 to 290%	negligible	• Rapid sludge disintegration • Significant increase in biogas m^3/kg_{VS} • Simple operation, external to sludge circuit • Suited to retrofit	• Laboratory scale demonstrated only • Suitability in continuous process • Unknown net energy gain	Shin and Kang 2003
γ-Ray	0 to 35%	negligible	• Rapid sludge disintegration • Part influent flow can be treated • Suited to retrofit	• Laboratory scale demonstrated only • Suitability in continuous process • Unknown safety issues • Unknown radio-contamination of effluent • Unknown net energy gain	Yuan *et al.* 2008

Table 3.6.1 (B) Effect of optimising techniques on sewage AD biogas volume and methane fraction

Technique	Δ% biogas volume	Δ% biogas CH_4 fraction	Benefits at Malabar STP	Concerns at Malabar STP	Source(s)
Substrate improvement					
AT sludge inoculation	0 to 150%	Negligible	• Significant increase in biogas m^3/kg_{VS} • Suited to retrofit • Minimal effect on biosolids processing	• Laboratory scale demonstrated only • Additional sludge heating circuit to produce AT sludge • Unknown net energy gain	Miah *et al.* 2005
Co-digested organics	0 to 40%	0 to 15%	• Reduced biosolids • Treatment of additional wastes • Compatible collection networks • Minor changes in operating procedure • Potential increased methane content by altered substrate composition	• Additional materials handling on site • Additional waste storage • Additional truck movements in area • Vector and vermin control • License restrictions • Additional odour issues for local community	Ahring 2003, California Energy Commission 2008
Sludge thickening (CAS)	0 to 10%	Negligible	• Existing CAS plant for sludge thickening • Extensive SW experience with CAS • Reduces solids loading of effluent to ocean	• Cost of chemical supply • Sludge handling plant capacity restricts primary solids capture to 60 %wt • Marginal increase in biogas m^3/kg_{VS}	Deublein and Steinhauser 2008, Sydney Water 2009b
Digester operation					
Mixing optimisation	0 to 10%	Negligible	• Minor scope of plant modifications • Recovery of biogas that is no longer required for compression and sludge mixing	• Difficulty and relatively high cost of accurate modelling or plant trialling to guide optimisation efforts and to measure their effect • Additional electrical load • Digester outages are likely to be required in order to make only minor modifications to the mixing system (i.e. hard to justify to plant operations staff)	Deublein and Steinhauser 2008

4. Research Methods

This section explains in detail how the specific questions raised during this research were answered. General information on methods for the literature review, plant familiarisation, and data collection is also provided.

4.1 Literature review

The initial aim of the literature review was to understand AD in primary sewage treatment and the sludge digestion plant at Malabar STP. It was considered that, in order to not miss any opportunity of increasing biogas volume or methane content, the review should follow the sludge through the whole process train from its receipt as raw influent through to its final forms; dewatered biosolids, treated effluent, and conversion to biogas.

The literature review then considered the following areas:

i) Detailed AD chemistry and microbiology.
ii) Previous work by SW on biogas optimisation.
iii) Recent academic research on biogas optimisation.
iv) Digester design principles.

Academic and industrial literature was obtained for review via a keyword abstract search of journal databases in Murdoch University library and in the public domain. Handbooks and conference presentations were obtained via internet search and library loan. Process guidelines, design rules, and STP asset reports were obtained from SW.

4.2 Malabar STP configuration

In order to understand the route of the sludge through Malabar STP it was necessary to obtain and read relevant plant arrangement drawings and process and instrumentation diagrams (P&IDs).

4.3 Operating data

The research used historical operating data from the cogeneration plant and sewage digesters as collected and stored by the SCADA system at Malabar STP. Each plant instrument is identified on P&IDs by a unique number known as its data point. All data points for analysis were selected after reading the P&IDs for Malabar STP concurrent with the literature review, and deciding which instruments measured process variables that were of interest.

As noted in Section 1.3 the SRT of Malabar STP digesters is 15 – 19 days. Operating data was recovered for the 7 day period 11th – 18th June 2010 at a uniform sampling rate of 16 minutes and 48 s throughout the period. It was judged from the literature review that this sampling rate and period were adequate to observe the relatively slower rates of change in the continuous AD process as well as to produce a manageable quantity of data. It was also considered that the digester's "worst case" operation would occur during winter, when low ambient temperatures maximise the heating load on the total biogas supply. The net biogas available for cogeneration in winter time would indicate the maximum scope for optimisation during the year.

The raw data was recovered from the SCADA system as a comma separated variable (CSV) file, opened as a spreadsheet, and checked for inconsistent measurements or continuous zeroing - such data was deleted. The checked data was then manipulated in a new spreadsheet to show graphical trends over time.

4.4 Answering research questions

The specific research questions raised in Section 2 are repeated below with a discussion of the method followed to answer each one.

4.4.1 Question 1

> *"What are the most viable means, including plant modifications or additional equipment, to achieve higher rates of biogas production within the overall constraints presented by Malabar's primary functions as a sewage treatment plant?"*

This question was answered by reference to the industrial and academic literature on AD of sewage sludge, by consideration of the process design and equipment in use at Malabar STP, by studying graphs of operating data described in Section 4.3, and by drawing informed conclusions about the most practical and economical methods to increase biogas volumes without upsetting the digestion regime.

4.4.2 Question 2

> *"What factors limit the maximum rate of biogas production by anaerobic digestion of a given sewage flow?"*

This question was answered by consulting the reviewed academic literature on sewage sludge AD and reaction kinetics.

4.4.3 Question 3

> *"What is the maximum sustained rate at which biogas could be produced at Malabar STP?"*

This question was answered by calculating a theoretical maximum biogas flow rate using a validated spreadsheet adapted to primary sewage sludge from the steady state AD model originally developed for slurried pig manure (Chen 1983).

Inputs to this calculation for Malabar STP were as follows:

i) The measured average VS fraction of 75 – 80% in the primary sludge.

ii) The typical digestion of 50% of VS in mesophilic AD of sewage sludge as shown in Figure 4.4.1 (Taricska *et al.* 2007).

iii) A total active digester volume in parallel operation of 35,000 m^3.

iv) A uniform and steady digesting sludge temperature of 35 ^oC.

v) The measured average methane fraction 65 %vol in biogas supplied to the cogeneration system.

vi) An historical methane yield of 0.5 m^3/kg_{VS} of digested volatile solids.

vii) An SRT of 15 days.

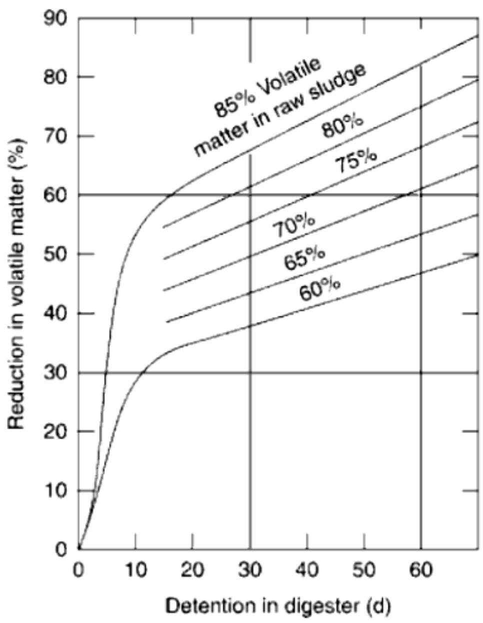


Figure 4.4.1 VS consumption in high rate mesophilic AD of sewage sludge
(Source: Taricska *et al.* 2007)

This calculation ignored correctable issues arising from the age of the real plant, such loss of active digester volume by sedimentation, and from short term variations in influent conditions such as solids concentration and storm flows.

A digester temperature of 35 ^{o}C was used because it was the maximum observed in actual digester temperatures at Malabar STP during the (winter) data collection period of this research. This temperature was also regarded as the optimum point in the range 32 – 38 ^{o}C for mesophilic AD (refer Section 3.2). Based on the digester sludge temperature profiles observed during this research it was considered reasonable to assume for this estimate that the digester heating system had the capacity (if not the necessary finer control) to maintain sludge temperature steady at 35 ^{o}C throughout the year.

An SRT of 15 days was used because it was on the conservative side of the design operating range of 15 – 19 days for Malabar STP.

Results of the calculation were represented as surface graphs in order to show the sensitivity of AD biogas production to changes in digester SRT, sludge temperature, and VS concentration.

It was then supposed that the single most viable optimising technique chosen in answer to Question 1 would be implemented. The calculated theoretical range of maximum flow rate was then multiplied by the average likely percentage increase in biogas volume from that technique as reported in Table 3.6.1.

Estimating biogas production from a digester's measured VSLR and VS destruction is a conventional method. Greater accuracy has been reported by some researchers using newer methods based on influent COD and COD destruction. Malabar STP primary sludge COD data was unavailable for this research.

4.4.4 Question 4

> "*What factors affect the ratio of methane to carbon dioxide in sewage biogas and how can these factors be optimised at Malabar STP?"*

The first part of this question was answered by consulting the academic literature on AD microbiology. The second part was answered by considering the process path of primary sludge through Malabar STP, by studying the graphs of digester and cogeneration system process conditions, and by then drawing informed conclusions about ways of potentially increasing the CH_4/CO_2 ratio by changing certain process parameters and the properties of the AD substrate.

4.4.5 Question 5

> "*How does biogas production at Malabar STP compare with benchmark performance data for anaerobic digestion of sewage sludge?"*

This question was answered by directly comparing published typical operating data for stable AD digesters fed with primary sewage sludge with the same operating data from Malabar STP.

5. Malabar STP Biogas Production

This section presents the operating data collected at Malabar STP as described in Section 4.3. Further description of specific data points and trends in plant function, discussion of background calculations, and any other necessary qualification of the data are provided throughout this section. Detailed interpretation and a critical analysis of the data and calculation results are presented in Section 6.

During the period of the collected data, primary sludge digestion was performed in Digesters 2 and 5. Digester 3 was used as a holding tank for digested sludge ahead of dewatering in the biosolids plant. Digesters 2 and 5 were operated continuously in parallel, with a total active volume of about 22,800 m^3. Both digesters had recently been cleared of grit carried over from the primary sedimentation tanks.

All three generator sets in the cogeneration system were operated continuously at various part loads throughout the period of the collected data.

5.1 Net biogas flow rate and cogeneration system output

Figure 5.2.1 shows the net biogas flow rate measured at the inlet to the cogeneration system's biogas conditioning skid (blue), and the total electrical output of the cogeneration system (orange). The total flow rate of biogas (green) drawn by the compressors for recirculation through all three digesters to mix the sludge is also shown. Measurements of flared biogas flow rate were not available.

It is important to note that Figure 5.2.1 shows the total volume flow rate of uncompressed biogas as measured in the take-off pipework from individual digester covers, and so may be compared directly with the net biogas flow rate to the cogeneration system that is drawn from the same locations. The rated electrical output of the cogeneration system (red) is also shown for reference. Each vertical gridline represents 12 hours during the period.

Large, sudden falls in the cogeneration system's electrical output are clearly *followed* by similar falls in biogas flow rate. This indicates that the loss of electrical load was caused by some operating factor other than an interruption in biogas fuel flow, which appears to have been correctly isolated in response. On these occasions the electrical load was quickly recovered while the biogas recirculation flow rate was maintained, indicating that the biogas supply was readily available throughout the period.

In summary, Figure 5.2.1 shows that the net combined biogas production of Digesters 2 and 5 was steady at about 375 L/s. This fuel flow was enough for a cogeneration system electrical output of about 2,250 kW_E or 74% of rated capacity. The total biogas recirculation flow rate through both digesters was steady at about 1,200 L/s, which was roughly 320% of the net biogas flow rate available to the cogeneration system.

5.2 Digester recirculated sludge temperature

Figure 5.2.2 shows digester sludge temperatures measured at the inlet of the recirculation pipework located at the base of each digester and leading to the sludge recirculation pumps. Each vertical gridline represents 12 hours during the data collection period.

The lower and lagging sludge temperatures measured in the unheated Digester 3 (red) confirm its use for storage of digested sludge being fed to the biosolids plant. The sludge temperature in Digester 3 was normally stable at between 25 – 26 ^{o}C.

The primary sludge in Digesters 2 (grey) and 5 (lime) appears to have experienced relatively large and rapid cycles of alternating forced heating and natural (i.e. free conductive and convective) cooling throughout the period. Temperatures in Digester 2 appear to be the most varied; ranging at times through 5 – 6 ^{o}C over the course of one day.

For a period of some 15 hours between about 20:00 on 15 June and 11:00 on 16 June Digester 2 appears to have been unheated; evident by a steady exponential decay in sludge temperature. Immediately after this period a similar but more sudden fall from about 25.5 ^{o}C to 22 ^{o}C may be seen in the temperature of sludge stored in Digester 3. This suggests that cooled digested sludge from Digester 2, mixed with digested sludge at around 33.5 ^{o}C from Digester 5, had been transferred into Digester 3 for storage. Sludge temperature in Digester 3 returned to around 25 ^{o}C within 4 – 5 hours of sludge heating being restored on Digester 2.

Numerous times the sludge temperature in Digester 2 spiked upwards to the same point at about 35 ^{o}C before immediately falling.

Digester 2 appears to have had no steady temperature during the data collection period, while Digester 5 does appear to have been maintained for up to several days at various temperatures between 33.5 – 34.5 ^{o}C, with excursions as low as 30.5 ^{o}C.

It is unlikely that the entire volume in either digester uniformly experienced the indicated temperature ranges owing to the thermal inertia of around 11,000 m^3 of sludge in each; but clearly some portion of the volume did, depending on how long the sludge was unheated. The nominal total recirculation sludge flow rate of either digester was 120 L/s, which meant that the combined volume of both would be turned over in about 24 hours. When the sludge temperature fell continuously by 5

– 6 ^oC during a 24 hour period, as was observed here on Digester 2, it is reasonable to conclude that most of the sludge in that digester did cool by this amount.

Figure 5.2.1 shows that the net biogas flow rate and the cogeneration system's electrical output both remained steady despite the sludge temperature variations. This suggests that the temperature variations only affected the long-term trend (i.e. over a number of months) in total average biogas production.

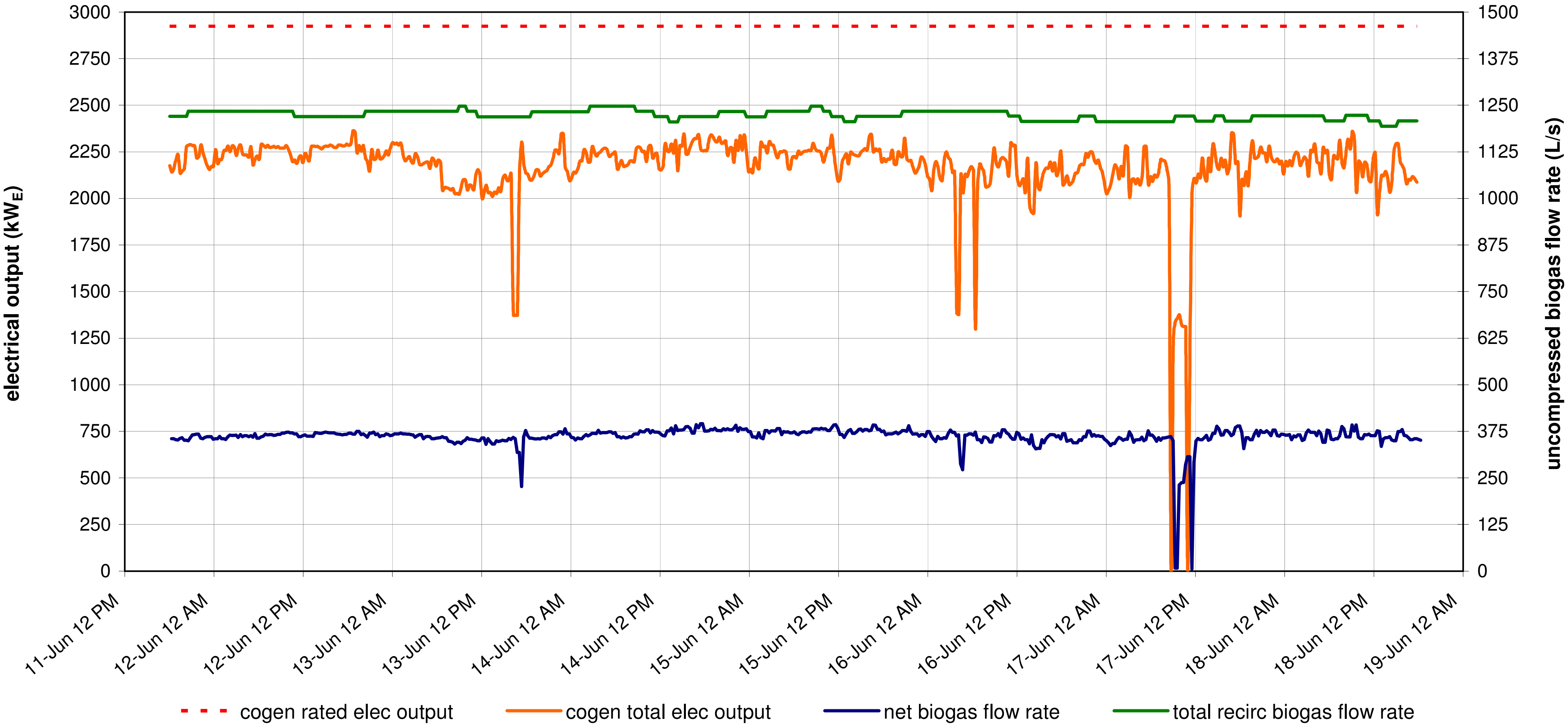


Figure 5.2.1 Malabar STP biogas net and recirculation flow rates, cogeneration electrical output 11 – 18 June 2010

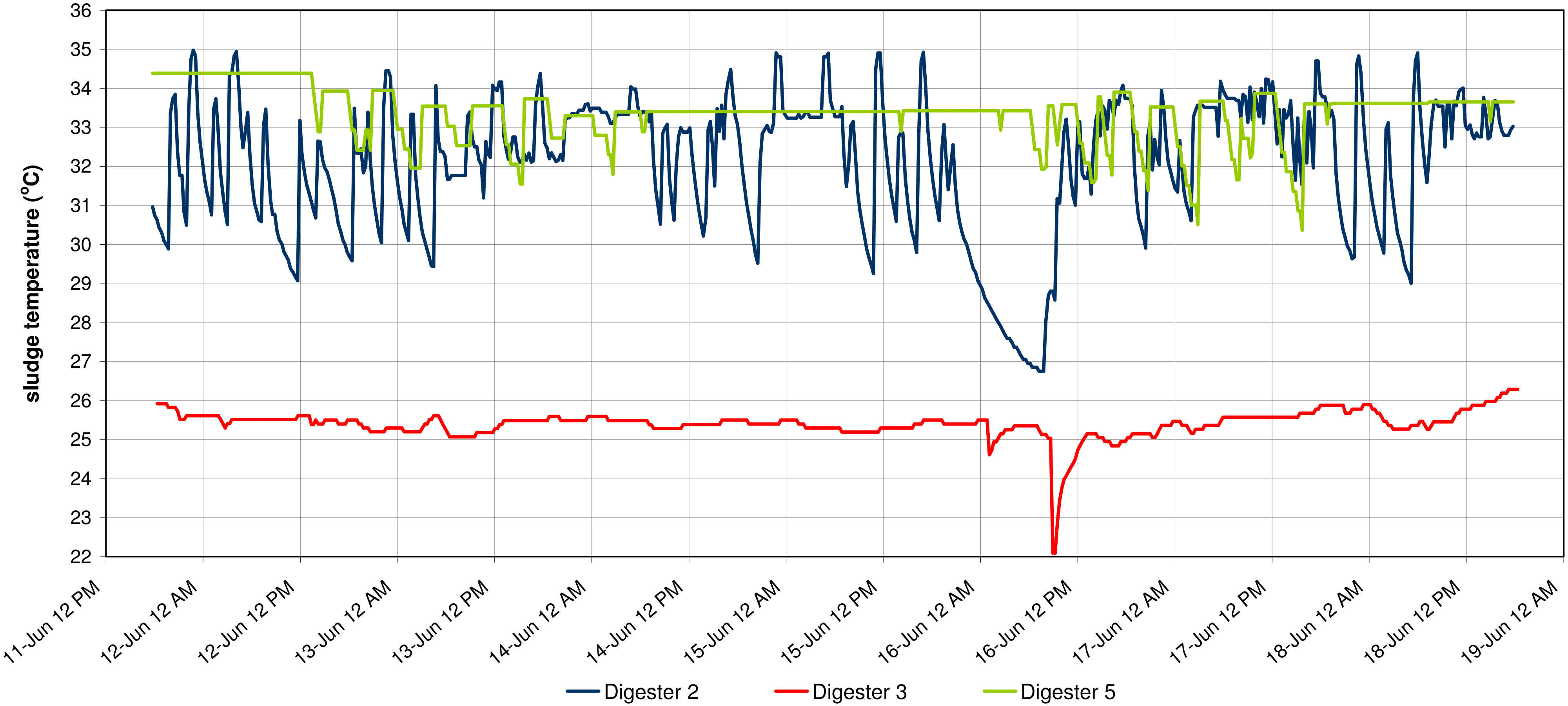


Figure 5.2.2 Malabar STP digester sludge recirculation temperatures 11 – 18 June 2010

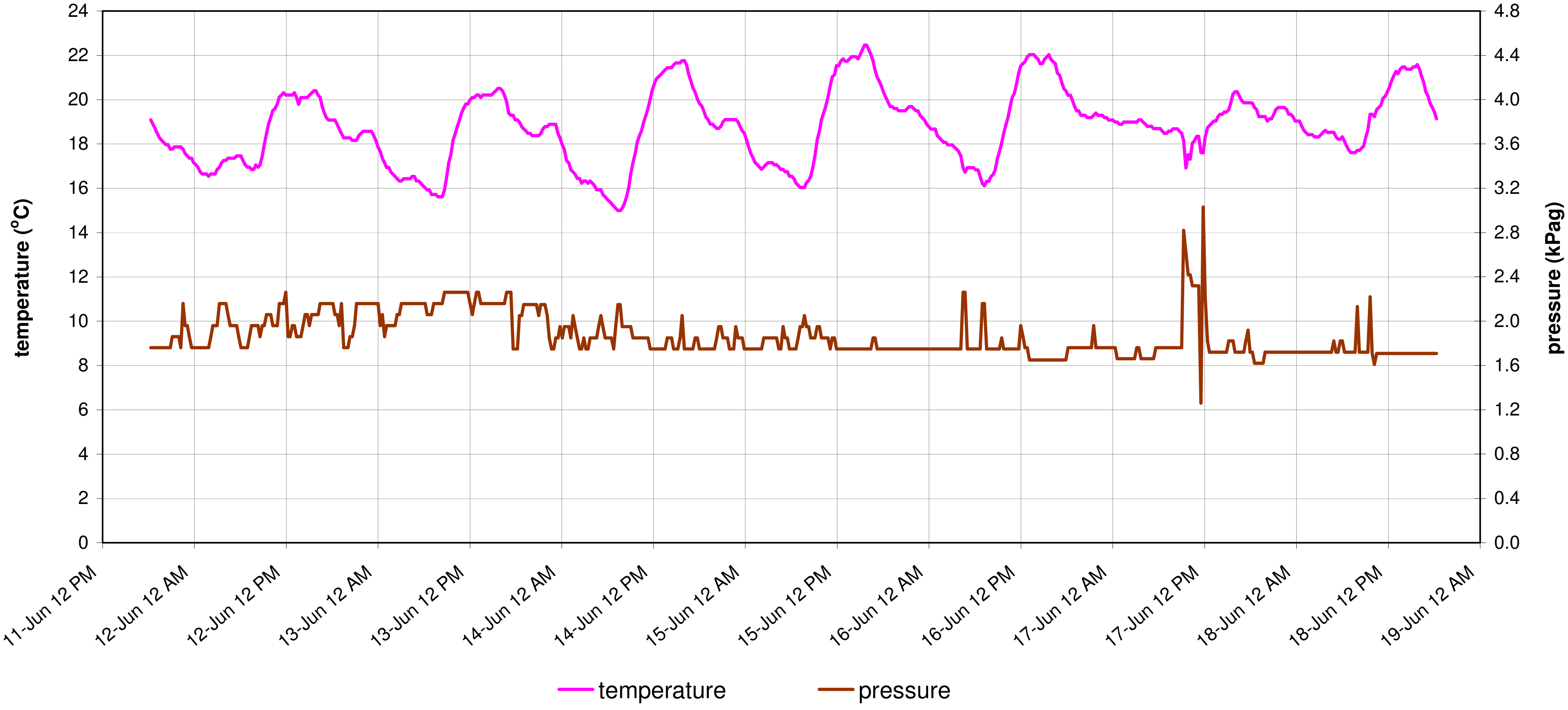


Figure 5.2.3 Malabar STP biogas temperature and pressure at cogeneration system inlet 11 – 18 June 2010

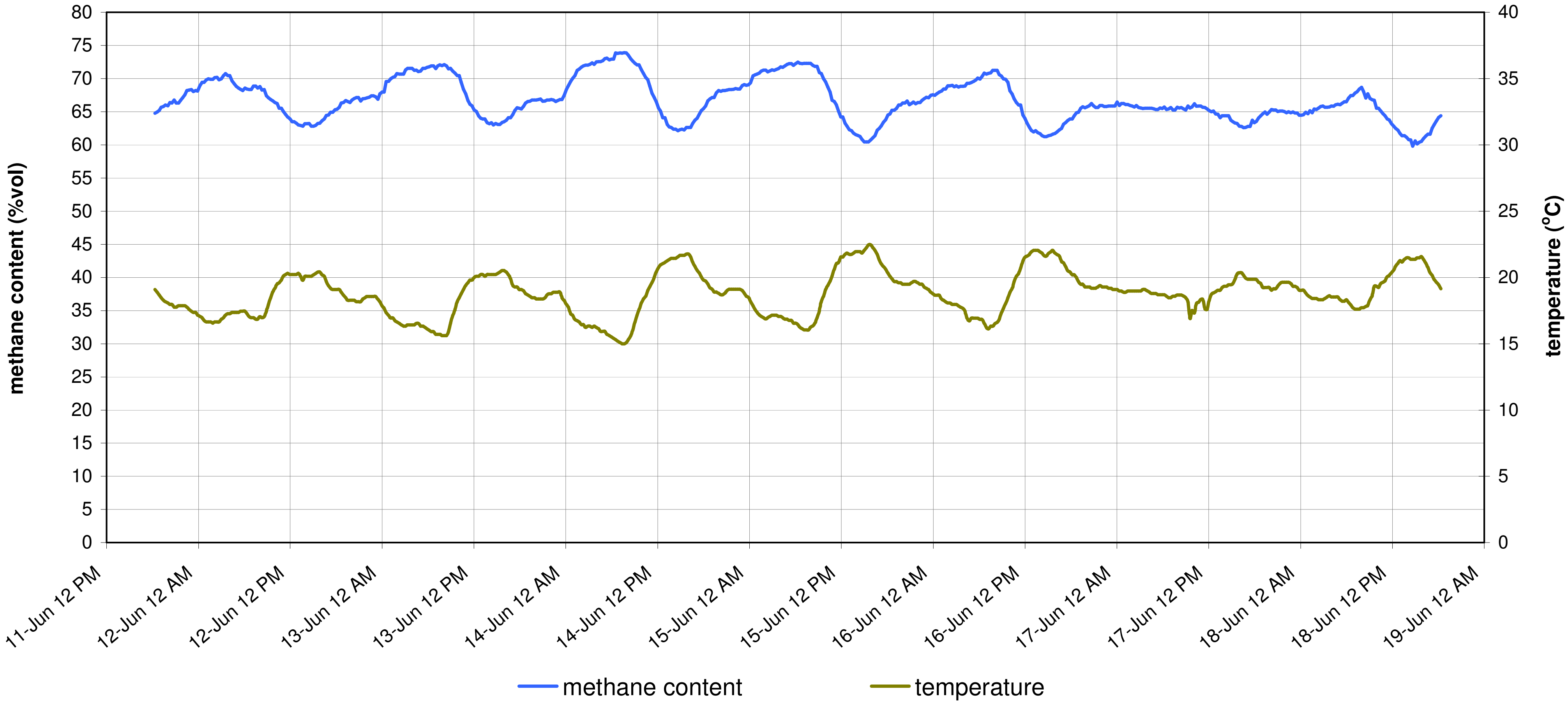


Figure 5.2.4 Malabar STP biogas methane content and temperature at cogeneration system inlet 11 – 18 June 2010

5.3 Biogas temperature and pressure

Figure 5.2.3 shows biogas temperature (pink) and pressure (brown) measured at the inlet to the cogeneration system's biogas conditioning skid.

The biogas temperature ranges between 22 ^{o}C and 14.5 ^{o}C. The temperature clearly follows a daily pattern of ambient heating and cooling as the biogas is transferred from the digester manifold to the cogeneration system inlet via an uninsulated pipe located above ground.

Biogas pressure at the cogeneration system inlet, and therefore throughout the upstream pipework from the digesters, was normally between 1.7 – 2.3 kPag during the data collection period. An exception was the loss of cogeneration system electrical output and subsequent isolation of the biogas supply just before 12:00 on 17 June. The instantaneous rise and fall in biogas pressure simply suggests that it was a rapid isolation.

The biogas pressure at the cogeneration system inlet during the data collection period was generally below the set point range of 2.2 – 2.6 kPag for maximum electrical output. As observed in Figure 5.2.1 and explained in Section 1.4 the cogeneration system automatically reduced its electrical output in response to these lower pressures and the corresponding reduced net biogas flow rate received from Digesters 2 and 5.

5.4 Biogas methane content and temperature

Figure 5.2.4 shows biogas volumetric methane content (blue) and temperature (khaki) measured at the inlet to the cogeneration system's biogas conditioning skid. The volumetric methane content shows the expected inverse relationship to biogas temperature. At a temperature of 20 ^{o}C the methane content was 65 %vol.

5.5 Digester performance

Certain operating points extracted from the measured data for Digesters 2 and 5 are summarised in Table 5.5.1, and compared with the benchmark data that were presented in Section 3.4. Some residual AD was likely to have continued in storage Digester 3 before the bacteria washed out of Digesters 2 and 5 died. Any additional biogas from this is not considered here since Digester 3 was effectively in a dynamic state and so unable to be compared with the benchmark steady state data.

Table 5.5.1 Malabar STP anaerobic digester performance 11 – 18 June 2010

Parameter	Units	Digester 2	Digester 5	Benchmark
Total solids in primary sludge	%wt	5		5 – 6
VSLR	$kg_{VS}/m^3/d$	4.7		1.6 – 4.8
Sludge temperature	^oC	26 – 35	31 – 34	32 – 38
Sludge temperature change	$^oC/d$	5 – 6	3 – 4	≤ 0.5
Biogas yield [1]	m^3/kg_{VS}	0.64		0.75 – 1.12

[1] Net of recirculation flow rate

The biogas yield is reported here on a net basis because, although the biogas recirculation flow rate was known, the combined flow rate of dissolved (compressed) biogas being removed with the digested sludge from active Digesters 2 and 5 and storage Digester 3 was unknown. The stability of both the net and recirculation biogas flow rates seen in Figure 5.2.1 suggests that the AD processes were able to supply this ‘replacement’ biogas.

5.6 Maximum possible steady state biogas production

The maximum possible net rate of biogas production under steady state conditions at Malabar STP was estimated using a steady state AD model that was based on VS destruction and loading rate in a continuously-stirred digester (Chen 1983). The model was developed for pig manure, but in the spreadsheet calculation used here the kinetic constants and methane yield for the model had been re-calibrated for typical sewage sludge from published data. Inputs to the calculation were as listed in Section 4.4.3 above.

Model input values and results of the biogas production estimate are shown in Table 5.6.1. All values in this table were calculated unless noted otherwise.

Table 5.6.1 Malabar STP maximum steady state biogas flow rate

Parameter	Units	Value
Total solids in primary sludge [1]	kg/d	131,200
VS fraction [1]	%	75 – 80
VS in primary sludge	kg/d	104,960
Primary sludge flow rate	m^3/d	2,333
Digester active volume [2]	m^3	35,000
SRT [2]	days	15
Digester operating temperature (constant) [2]	^oC	35
VS concentration [1]	kg_{VS}/m^3	45
VS digested#	%wt	50
Methane yield per unit of VS in primary sludge [3]	m^3/kg_{VS}	0.50
Methane flow rate	m^3/d	27,440
Methane fraction [1]	%vol	65
Carbon dioxide flow rate	m^3/d	14,770
Maximum steady state biogas flow rate	m^3/d	42,200
	L/s	490
Biogas yield per unit of VS digested	m^3/kg_{VS}	0.77
Methane yield per unit of primary sludge	m^3_{CH4}/m^3	11.8

[1] Data measured during this research
[2] Design or typical data
[3] Historical data

The estimated maximum steady state biogas flow rate at operating temperature 35 ^oC and VS concentration 45 kg_{VS}/m^3 is 490 L/s with methane fraction of 65 %vol.

Table 5.6.2 shows the potential electrical output of the cogeneration system operating on a net steady state biogas flow rate of 490 L/s containing 65 %vol methane. In this calculation the generating sets are assumed to convert the biogas to electricity with an average efficiency of 26% (recovered heat is not included in this). The estimate also assumed that, once established, the total recirculation biogas flow does not need to be replenished, so that all of the biogas produced in steady state operation is net available to fuel the cogeneration system.

Table 5.6.2 Malabar STP cogeneration system potential electrical output

Parameter	Units	Value
Methane energy content [1]	MJ/m^3	39.0
Methane flow rate	m^3/d	27,440
	m^3/s	0.32
Energy available for cogeneration	MW	12.5
Cogeneration efficiency (electrical) [3]	%	26
Potential electrical output	kW_E	3,245
Rated electrical output [2]	kW_E	2,925

[1] Data at 35 °C and 1.5 kPag (digester operating conditions)
[2] Design or typical data
[3] Assumed data

The potential electrical output under these conditions is 3,245 kW_E compared with the rated system output of 2,975 kW_E.

Results of the calculation in Table 5.6.2 indicate that it is theoretically possible to produce enough biogas in the existing Malabar STP digesters to operate the cogeneration system at its rated load all of the time. This quantity of biogas would be produced from typical Malabar STP influent sewage using the existing primary sedimentation system without CAS or other pre-treatment. A slight excess of biogas could even be expected to be flared under steady state conditions.

On the strength of this calculation no additional measures to increase biogas production appear to be necessary: Digester 3 has only to be reverted to active sludge digestion rather than being used to store digested sludge from Digesters 2 and 5. Still, following the approach outlined in Section 4.4.3, application at Malabar STP of what is currently the most viable biogas optimisation technique - ultrasonic pre-treatment, as described in Section 3.5.3 and Table 3.6.1 - could yield an additional 20% biogas for a total flow of 42,200 × 1.2 = 50,600 m^3/d.

The sensitivity of this estimate to VS concentration, digester operating temperature, and SRT was investigated to see what methane production may be possible within the fixed capacity of the Malabar STP digesters, when fed with the measured VS content of primary sludge pumped from the existing sedimentation tanks.

Figure 5.6.1 is a surface graph of AD methane yield per unit volume of primary sludge as a function of VS concentration and SRT at Malabar STP during AD at a steady uniform temperature of 35 ^{o}C throughout the digesters.

Figure 5.6.2 is a surface graph of AD methane yield per unit volume of primary sludge as a function of digester temperature and SRT at Malabar STP during AD of primary sludge having a constant VS concentration of 45 kg_{VS}/m^3.

Figures 5.6.1 and 5.6.2 together show how biogas methane yield would change in response to variations in VS concentration, digester temperature, and SRT.

In both Figures 5.6.1 and 5.6.2 the methane yield of 11.8 m^3_{CH4}/m^3 of primary sludge that was estimated in the Table 5.6.1 calculation is confirmed to be within the plotted range of 10 – 15 m^3_{CH4}/m^3.

Figure 5.6.1 shows how methane yield changes with variations in VS concentration and SRT at constant sludge temperature 35 ^{o}C. In general, longer retention times with sludge of any given VS concentration lead to a higher methane yield from a given volume of primary sludge. At sludge temperature of 35 ^{o}C the model indicates that there is an optimum VS concentration of 40 – 60 kg_{VS}/m^3 for maximum methane yield and that within this range SRT has minimal effect. At VS concentrations outside the range 30 – 70 kg_{VS}/m^3 the model indicates that the biogas methane yield is substantially reduced regardless of SRT (up to 23 days). This is consistent with the effects of organic under- and over-loading conditions on actual digesters.

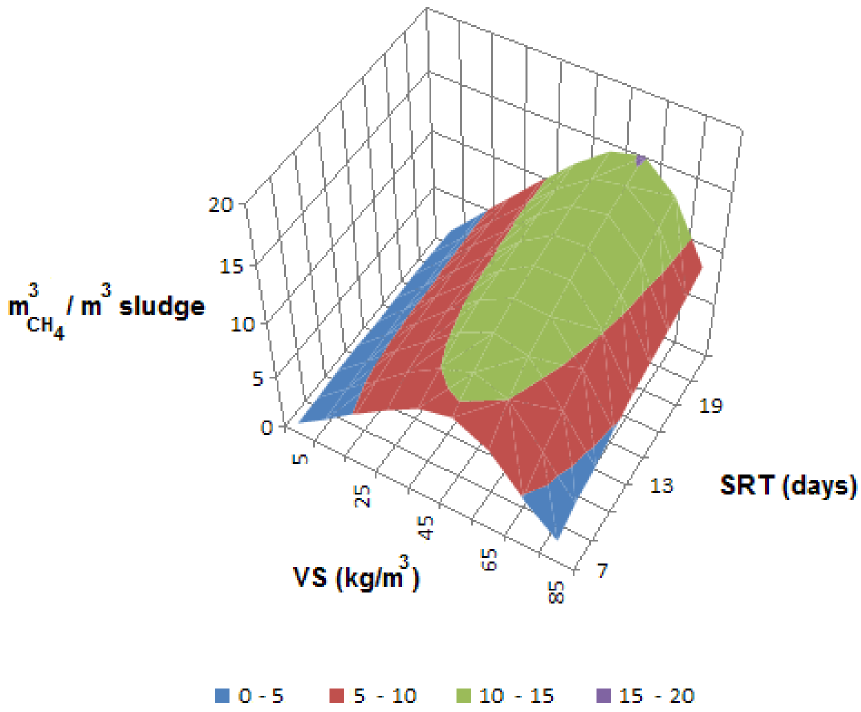


Figure 5.6.1 Malabar STP methane yield per unit volume of primary sludge at temperature 35 °C

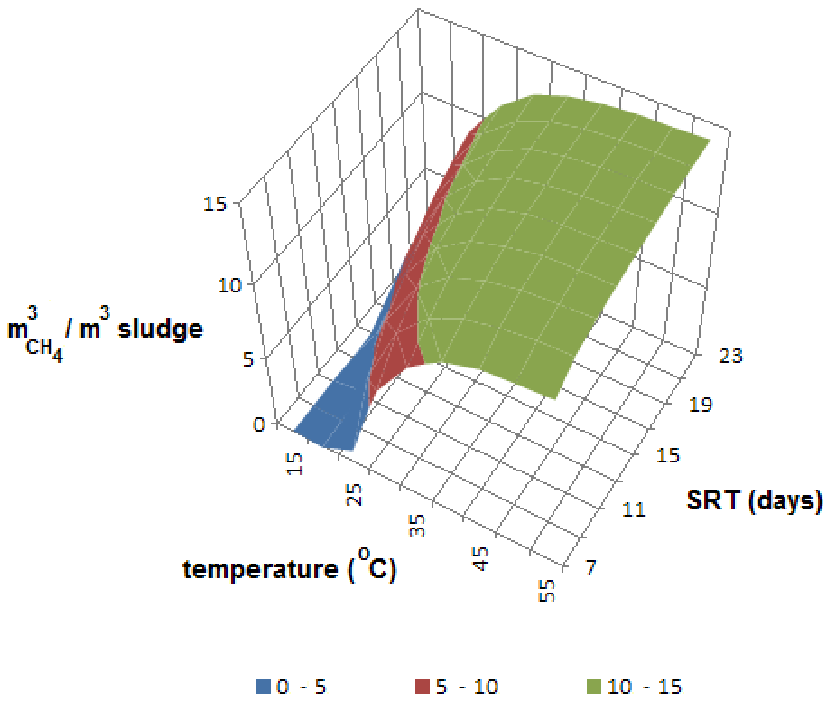


Figure 5.6.2 Malabar STP methane yield per unit volume of primary sludge at volatile solids concentration 45 kg_{VS}/m^3

Figure 5.6.2 shows how methane yield changes with variations in sludge temperature and SRT at the constant VS concentration of 45 kg_{VS}/m^3 that was observed in the primary sludge at Malabar STP during this research. It is clear from this that a mesophilic anaerobic colony will have a low reproduction rate at temperatures below about 20 ^oC regardless of VS concentration or SRT. At the opposite (right hand) side of the graph, a slight increase in biogas methane yield would be expected from increasing the sludge temperature above 35 ^oC, together with ever-decreasing gains in methane yield as SRT is steadily increased (up to 23 days).

Both Figures 5.6.1 and 5.6.2 suggest that, given the plant's physical constraints, the actual operating conditions at Malabar STP of a nominal (but apparently unstable) sludge temperature 35 ^oC, VS concentration 45 kg_{VS}/m^3, and SRT of 15 – 19 days are near to a practical optimum combination of these three important variables of AD.

6. Discussion

This section presents an interpretation of the data in Section 5. It offers a critical analysis of the potential for increased biogas production at Malabar STP in view of other researchers' findings as reviewed in Section 3. This section also discusses the significance and limitations of the data, the limitations of the research methods, and the extent to which the aims of the research were achieved.

Answers to the research questions are developed in this section then stated as explicit conclusions in Section 7.

6.1 Digester temperatures

Sludge temperatures in Digesters 2 and 5 observed over 11 – 18 June showed unexpected variability. This could indicate any one or a combination of the following:

i) Rapid stopping and re-starting of sludge recirculation and local cooling only of sludge stopped next to the measurement point, while the temperature of the majority of sludge remained stable.
ii) Temperature stratification within the digester while the sludge recirculation and biogas mixing flows were steady.
iii) Delays in supplementary biogas firing of the digester heaters following reduced heat input from the engine jacket water systems, in response to low biogas flow rate or some other operating problem.
iv) Instrument faults.

In any of these cases except the last, the sludge temperature variation observed in both Digesters 2 and 5 would inhibit methanogenesis and contribute to VFA instability. As the comparison in Table 5.5.1 makes clear; temperature changes in these digesters of up to ± 6.0 ^{o}C/d are well beyond the recommended figure of ± 0.5

^{o}C/d or less for stability of the bacterial colony as found by other researchers (Table 3.4.1).

The thermal inertia of such large volumes of water as held in Digesters 2 and 5 makes it unlikely that the temperature variations seen in Figure 5.2.2 were representative of or uniform throughout the entire volume of primary sludge in each. But as discussed in Section 5.2; during periods of 12 or more hours of steady decay in temperature during which sludge was being recirculated it is certain that a significant portion of the sludge experienced temperature variations larger than the recommended ± 0.5 ^{o}C/d.

AD researchers have consistently reported on the need for temperature stability during methanogenesis. It is reasonable to conclude that the variation observed here in Digesters 2 and 5 reduced the biogas yield and the net biogas flow rate to the cogeneration system. This finding is confirmed by the result of the estimate of maximum potential biogas flow rate at a *steady* temperature of 35 ^{o}C - equal to the *maximum* temperature observed in Figure 5.2.2. The biogas yield for the steady temperature was estimated to be 0.77 m^3/kg_{VS} (Table 5.6.1); or approximately 20% greater than the yield of 0.64 m^3/kg_{VS} (Table 5.5.1) that was observed with some portion of the sludge affected by temperature variations of up to ± 6.0 ^{o}C/d. There is no reason to think that the plant performance seen during this research is atypical, and that reduced net biogas production doesn't persist all year as a result.

The profile of the temperature spikes in Figure 5.2.2 is notable. They show the sludge temperature in Digesters 2 and 5 repeatedly falling gradually at a reducing rate but increasing suddenly and almost linearly; and all of this apparently occurring at random. These trends indicate relatively long periods of no heating, rather than a lack of heating capacity that would be able to maintain a steady temperature. Possible reasons for this behaviour include:

i) An excessive time lag on the biogas heaters' purge and ignition sequence upon receipt of a low sludge temperature signal – possibly meant to reduce either fluctuations in flow rate and pressure throughout the raw biogas network or wear and tear on the biogas heaters themselves.

ii) Poorly calibrated or faulty pressure switches in the biogas heaters' fuel lines erroneously indicating no fuel present to start on receipt of a low sludge temperature signal.

Such issues as these would be a matter for regular maintenance of the equipment and fine-tuning of plant controls.

In summary; greater sludge temperature stability in Digesters 2 and 5 has good potential to increase biogas yield and the net flow of biogas available for cogeneration by some 20%. An average temperature of 32 – 35 ^{o}C should be maintained and rapid variations around this value should be eliminated.

6.2 Other digester operations

Figure 5.2.1 shows the nominal total biogas recirculation flow rate is 1,200 L/s. This flow was continually compressed and re-injected into Digesters 2, 3, and 5 for sludge mixing, then drawn out of the covers for re-compression. The biogas recirculation flow rate of 1,200 L/s compares with the net biogas flow rate of 375 L/s left over for fuelling the cogeneration system.

The recirculation biogas flow is built up over months during initial start-up of a digester and, once established, is adjusted with day-to-day changes in sludge level, temperature, and other operating variables. As noted in Section 5.5, a portion of the net biogas production is needed to replace recirculation biogas that is continually removed in solution with digested sludge, or periodically removed with the net biogas flow when the sludge level falls. Were some other method of sludge mixing employed, additional biogas would become available for cogeneration and the overall net biogas flow would be more even. Alternatives could include submersible mechanical (propeller) mixers or additional sludge recirculation pumps internal to the digester. Given the large volumes to be mixed these devices would be likely to add a significant new electrical load at the site which may not be covered by any gain in cogeneration system electrical output.

Malabar STP digesters occasionally suffer biogas leaks in the seal between the floating cover and the side wall. Leaks result in biogas escaping out of the cover into the atmosphere. Obviously, this reduces the volume of biogas available for cogeneration, but repairs involve lengthy digester outages and heavy-lift cranes to remove the cover.

6.3 Increasing biogas production

The estimate in Section 5.6 of maximum possible steady state biogas production reveals two salient points on increasing current biogas flows.

The first is that the total volume of primary sludge in Digesters 2 and 5 alone does not provide enough substrate to sustain an AD bacterial colony capable of converting enough VS into a biogas flow rate sufficient to fuel the cogeneration system at rated output, as observed in Figure 5.2.1. The estimated maximum possible biogas flow rate of 490 L/s is based on all three digesters being in service at very similar average operating conditions to those observed. As shown in Table 5.6.2, a biogas flow rate of 490 L/s and 65 %vol methane would be adequate to fuel the cogeneration system at rated load. Therefore it can be concluded that, with all other process conditions being equal, providing more sludge volume by returning Digester 3 to active AD will dramatically increase the net flow rate of biogas.

The second is the effect of temperature variations as discussed in Section 6.1. The estimated biogas yield of 0.77 m^3/kg_{VS} from digesting sludge at steady temperatures of 35.0 ± 0.5 ^{o}C/d is about 20% greater than at temperatures of 35.0 ± 6.0 ^{o}C/d with all other operating parameters the same (sludge volume, total and volatile solids concentrations, SRT, VS fraction converted to biogas).

Table 3.6.1 gives a qualitative assessment of the viability of techniques for increasing biogas production at Malabar STP. Many of these techniques have not yet been commercialised for sewage treatment, although their principles have been demonstrated in a laboratory setting using small, static batch volumes of sludge. Such demonstrations are not intended to also deal with the complicating factors of fluid mixing, VSLR dynamics, digested sludge removal, ambient temperature variations, physical and chemical contaminants, equipment wear and failure, and uneven sludge heating that regularly affect real anaerobic digesters. Electron beam, γ-ray, and microwave irradiation are readily applied to 1 – 2 L flasks of tailored substrate: the problem remains to apply these pre-treatments to large and continuous flows of primary sludge, having variable total solids and VS concentrations, in an industrial environment.

Of all the pre-treatment techniques considered the exposure of primary sludge to ultrasonic energy appears to offer the most benefit to SW at Malabar STP. This is a commercialised technology that has been demonstrated at other STPs to increase biogas yields from primary sludge by up to 40%. It would have an added benefit at Malabar STP of reducing the mass loading on the biosolids processing plant, leading to fewer truck movements around neighbouring suburbs in order to dispose of the biosolids offsite. Ultrasonic pre-treatment equipment would be installed upstream of the digesters; a likely location would be on the discharge pipework from the primary sludge transfer pumps where the flow is turbulent and well-mixed, rather than in a straight section of pipe further downstream (most of which is buried anyway). This should ensure maximum VS exposure to the ultrasonic dose.

All optimising techniques other than food waste co-digestion have no effect on methane fraction. Food waste co-digestion alters the chemical structure of the AD substrate by increasing carbohydrates and fats, which both have higher methane yield and are digested faster than the lipids and proteins that are prevalent in sewage sludge. Establishing food waste co-digestion at Malabar would need to start with a cost-benefit analysis that considers specific wastes. It is likely that those wastes with the lowest transport and handling costs to SW will be most attractive regardless of any increase in actual biogas yield and methane fraction. The analysis should look at wider implications for the treatment process including:

i) At what ratios the food waste is best mixed with primary sludge to prevent blocking pipes, pumps, etc.
ii) How and at what point in the treatment process the waste is introduced.
iii) What pulping and shredding may be necessary before introducing the waste.
iv) What changes in VFA, SRT, pH, alkalinity, and other digester control parameters are likely to be required.
v) Changes in biosolids plant solids loading.
vi) Effects on effluent quality ahead of the ocean outfall system.

The metropolitan setting of Malabar STP would seem to increase the range of wastes available nearby that could be examined for their co-digestion potential.

Increased biogas flows from any measure are likely to require either the installation of larger flares or an upgrade of existing flares to safely handle the extra biogas during cogeneration system outages.

6.4 Limitations of data

In general the selected data points enabled sufficient analysis to answer the research questions. Greater accuracy may have been possible in estimating maximum possible biogas yield by using data on the COD (instead of VS) content of the primary sludge had it been available. The sampling rate of 16 minutes and 48 s over a period of one week gave satisfactory resolution of digester trends relative to the SRT of 15 – 19 days and, as was discovered, temperature changes of $\pm$ 6.0 ^{o}C/d.

Some pressure sensors and flow meters in different parts of the LP biogas and sludge recirculation system returned zero readings (e.g. biogas flow and methane content at the waste gas flares, sludge heat exchanger return temperatures). This indicated no signal or some other configuration error, and so narrowed the view into the digesters' performance.

Several problems arose from the use of historical data recorded with plant instrumentation. Chief among these was uncertainty over the history of particular instruments, their calibration and functional status, and their exact physical location in the treatment process – which is normally only shown schematically on P&IDs. But given cost and time constraints there were few alternatives. On the other hand, an advantage of this approach was the ability to view trends and model the macroscale behaviour of an industrial high rate digester, rather than attempt to infer full-scale effects from, say, more precise laboratory batch tests.

6.5 Research methods

The research methods were generally suitable. An extensive and current academic and industrial literature on anaerobic digestion of sewage sludge was found, as expected, and formed a sound basis for interpreting the data collected from Malabar STP.

It had been intended to compare actual biogas production from similar anaerobic digesters to those of Malabar STP. This plan floundered for the unforeseen lack of suitably detailed data published by other utilities. Instead, benchmark design data were used for comparison; an approach that was probably more suitable in the end since the wide variation in plant configuration and equipment age in real STPs would have made for a difficult comparison.

It would have greatly improved this research to have had more time at Malabar STP to simply observe day-to-day treatment processes and to gain insight from the plant operator’s experience with AD biogas production.

6.6 Research aims

The primary objective of this research was to find ways to improve the load factor of the Malabar STP cogeneration system, by making more biogas available to it for more of the time; without forgetting that the purpose of Malabar STP is to continue providing cost-effective primary sewage treatment. This objective was mostly achieved, but further investigations should be made as recommended in Section 8.

7. Conclusions

This section presents conclusions about AD biogas production from sewage at Malabar STP in answer to the research questions set out in Sections 2 and 4.

Many sewage pre-treatment techniques have been the subject of academic study over the past 5 – 10 years. Most of these have been shown to increase biogas volume yield at the scale of a laboratory apparatus. The technical and commercial viability of almost all these techniques at an industrial scale remains uncertain.

The methane fraction of biogas is determined by the redox potential of the anaerobic reactions occurring in a digester maintained at particular temperature and pressure. For all practical purposes in mesophilic AD; the redox potential depends only on the chemical composition of the substrate rather than on process conditions.

The maximum rate of biogas produced by AD of sewage sludge is limited by the mass of sludge being digested, the temperature of digestion and its time rate of change, the concentration of easily digested intercellular organics (as opposed to total solids concentration) in the sludge, the solids retention time, the extent of forced mixing, and the presence of contaminants including VFAs. All of these factors impact on methanogenesis as the rate limiting stage in AD microbiology.

Malabar STP biogas yield is currently 0.64 m^3/kg_{VS} which is below the benchmark range of 0.75 – 1.12 m^3/kg_{VS} for AD. The VSLR and total solids concentration of the primary sludge feed are both within benchmark ranges. The low biogas yield is due to excessive temperature changes of up to ± 6.0 ^oC/d during sludge digestion compared with a benchmark rate of just ± 0.5 ^oC/d.

The maximum possible steady state biogas flow rate at Malabar STP was estimated to be 490 L/s or 42,200 m^3/d, containing 65 %vol methane, produced from Digesters

2, 3, and 5 working in parallel with a combined sludge volume of 35,000 m^3. The operating conditions in this scenario would be steady digester temperatures of 35.0 ± 0.5 $^oC/d$ and primary sludge volatile solids content 45 kg_{VS}/m^3, of which 50 %wt would be converted to biogas. This flow is adequate to fuel the cogeneration system operating at its continuous rated electrical output of 2,925 kW_E.

Additional primary sludge thickening by CAS or other methods is unlikely to be a viable means of increasing biogas production because the downstream sludge and biosolids handling plant cannot process the quantity of digested sludge that would result from digesting primary sludge having more than 55 – 60 kg/m^3 of total solids. Instead, sludge thickening would be likely to either overload the digester or lead to no net gain in biogas production because some SRT lower than the present 15 – 19 days would be necessary to prevent overloading.

The single most viable way to increase biogas production at Malabar STP is to reinstate Digester 3 as an active volume for sludge digestion, rather than continue using it for storing digested sludge from Digesters 2 and 5. This would result in about 120 L/s or 10,300 m^3/d of additional biogas; a gain of some 32% over the current net flow rate from Digesters 2 and 5. Extra volume for storage of digested sludge if required would appear to be better provided by enlarging or replicating the existing digested sludge storage tank, since Digester 3 is already configured for AD, and has sludge mixing, sludge transfer, and biogas collection systems in place.

Reducing sludge temperature changes in Digesters 2 and 5 to within ± 0.5 $^oC/d$ should improve biogas yields by up to 20%. Other viable ways to increase biogas production still further are food waste co-digestion, sludge pre-treatment by ultrasonic irradiation, and use of mechanical mixers in place of compressed biogas.

8. Recommendations

This section makes recommendations on further work to increase biogas production at Malabar STP in view of findings from this research.

i) Reinstate Digester 3 for primary sludge AD.

ii) Investigate and verify the correct functioning and calibration of sludge temperature sensors and sludge heater controls on Digesters 2 and 5 (and 3 if reinstated) in order to minimise sludge temperature variations.

iii) Trial ultrasonic pre-treatment of primary sludge through a risk-reward style contract with a design-and-construct technology provider. The provider could retain ownership of the equipment and pay themselves out of the savings SW makes on reduced import of grid electricity through higher biogas production. The equipment could be installed on either the primary sludge feed or recirculation pipework.

iv) Investigate food waste co-digestion. This could include trialling of domestic insinkerator maceration units at source throughout the Malabar STP sewage catchment, and diversion of grease-trap waste trucks, etc. working in the local area. Any waste should be blended with the sewage before being fed to the digesters.

v) Regularly calibrate and maintain pressure switches and transmitters within the biogas circuit.

vi) Investigate reducing or eliminating the need for biogas to be diverted to the compressors for digester mixing. Propeller-style, submersible mechanical mixers and pumps are the most viable alternative.

vii) Maximise active digester volume and SRT by regularly removing accumulated sunken grit and floating scum.

9. References

Ahring B. K., *Perspectives for Anaerobic Digestion*, Advances in Biochemical Engineering and Biotechnology (2003), Vol. 81

Axaopoulos P., Panagakis P., Tsavdaris A., and Georgakakis D., *Simulation and Experimental Performance of a Solar-Heated Anaerobic Digester*, Solar Energy (2001), 70(2):155-164

Bagi Z., Ács N., Bálint B., Horváth L., Dobó K., Perei K. R., Rákhely G., and Kovács K., *Biotechnological Intensification of Biogas Production*, Journal of Applied Microbiology and Biotechnology (2007), 76:473-482

Batstone D. J., *Mathematical Modelling of Anaerobic Reactors Treating Domestic Wastewater: Rational Criteria for Model Use*, Reviews in Environmental Science and Biotechnology (2006), 5:57-71

BiogasMax, *Best Practices in Europe,* European Biomethane Fuel Conference, http://www.biogasmax.eu/media/1p2_biogasmax_best_practices__021032800_0649_30092009.pdf, accessed online May 2010

California Energy Commission, Public Interest Energy Research Program (PIER), *Project 3.1 Co-Digestion of Dairy Manure/Food Processing Wastes and Biosolids Food Processing Wastes to Energy – Final Report* (2008), CEC-500-2007-015

Central Intelligence Agency, *World Factbook 2010*, https://www.cia.gov/library/publications/the-world-factbook, accessed online December 2010

Chen Y. R., *Kinetic Analysis of Anaerobic Digestion of Pig Manure and its Design Implications*, Agricultural Wastes (1983), 8:65-81

Clean Energy Council of Australia, *Australian Bioenergy Roadmap – Biomass Resource Appraisal* (2008)

Clean Energy Council of Australia, *Clean Energy Australia 2010*, http://www.cleanenergycouncil.org.au/dms/cec/reports/clean-energy-australia/B--Clean-Energy-Australia-Report-2010/B.Clean Energy Australia report 2010.pdf, accessed December 2010

Cui R. and Jahng D., *Enhanced Methane Production from Anaerobic Digestion of Disintegrated and Deproteinized Excess Sludge*, Biotechnology Letters (2006), 28: 531-538

Demirel B. and Scherer P., *Roles of Acetotrophic and Hydrogenotrophic Methanogens during Anaerobic Conversion of Biomass to Methane: A Review*, Reviews in Environmental Science and Biotechnology (2008), 7:173-190

Deublein D. and Steinhauser A., *Biogas from Waste & Renewable Resources: An Introduction* (2008) Wiley-VCH, Weinheim

EurObserv'ER, *Baromètre Biogaz*, Le Journal des Ènergies Renouvelables, No. 200 (2010), Systèmes Solaires

Gavala H., Angelidaki I., and Ahring B., *Kinetics and Modelling of Anaerobic Digestion Process*, Advances in Biochemical Engineering / Biotechnology Vol 81 (2003) Springer-Verlag, Berlin

Gerber M. and Span R., *An Analysis of Available Mathematical Models for Anaerobic Digestion of Organic Substances for Production of Biogas* (2008), International Gas Union Research Conference

Haandel A. van, Kato M. T., Cavalcanti P. F. F., and Florencio L., *Anaerobic Reactor Design Concepts for the Treatment of Domestic Wastewater*, Reviews in Environmental Science and Biotechnology (2006), 5:21-38

International Water Association, *Anaerobic Digestion Modelling Working Group*, http://www.iwahq.org/Home/Networks/Specialist_groups/List_of_groups/Anaerobic_Digestion/Anaerobic_Digestion_Modelling_Working_group/, accessed online July 2010

Kovács K. L., Kovács A. T., Maróti G., Bagi Z., Csanádi G., Perei K., Bálint B., Balogh J., Fülöp A., Mészáros L., Tóth A., Dávid R., Latinovics D., Varga A., and Rákhely G., *Improvement of Biohydrogen Production and Intensification of Biogas Formation*, Reviews in Environmental Science and Biotechnology (2004), 3:321-330

Kuang Y., *Enhanced Anaerobic Degradation of Lipids in Waste Water by Addition of Co-Substrate* (2002) Doctoral Thesis, School of Environmental Science, Murdoch University

Latha S., Borman D., and Sleigh P. A., *CFD Multiphase Modelling for Evaluation of Gas Mixing in an Anaerobic Digester*, 14th European Biosolids and Organic Resources Conference (2009)

Miah M. S., Tada C., Yang Y., Sawayama S., *Aerobic Thermophilic Bacteria Enhance Biogas Production*, Journal of Material Cycles and Waste Management (2005), 7:48-54

O'Flaherty V., Collins G., and Mahony T., *The Microbiology and Biochemistry of Anaerobic Bioreactors with Relevance to Domestic Sewage Treatment*, Reviews in Environmental Science and Biotechnology (2006), 5:39-55

Pérez-Elvira S. I., Nieto Diez P., and Fdz-Polanco F., *Sludge Minimisation Technologies*, Reviews in Environmental Science and Biotechnology (2006), 5:375-398

Pind P.F., Angelidaki I., Ahring B. K., Stamatelatou K., and Lyberatos G., *Monitoring and Control of Anaerobic Reactors*, Advances in Biochemical Engineering / Biotechnology Vol 82 (2003) Springer-Verlag, Berlin

Qiao W., Wang W., Zhu C. P., and Zhang Z. Z., *Biogas Recovery from Microwave Heated Sludge by Anaerobic Digestion*, Science China, Technological Sciences (2010), 53:144-149

Shin K. S., and Kang H., *Electron Beam Pretreatment of Sewage Sludge before Anaerobic Digestion*, Applied Biochemistry and Biotechnology (2003), Vol.109:227-239

Stamatelatou K., Lyberatos G., Tsiligiannis C., Pavlou S., Pullammanappallil P., Svoronos S. A., *Optimal and Suboptimal Control of Anaerobic Digesters*, Environmental Monitoring and Assessment 2 (1997) 355-363

Sydney Water, Asset Planning (Treatment), *Malabar STP Asset Management Plan* (2004)

Sydney Water, Unit Process Guideline, *Sludge Mesophilic Anaerobic Digestion,* North Head STP ref. UPG-1005-015 (2007)

Sydney Water, Asset Information, Systems & Standards, *STP Criteria Manual, Process Guidelines / Specifications, Group 4 – Standards & Specifications* (2009a)

Sydney Water, Asset Information, Systems & Standards, *STP Criteria Manual, Process Guidelines / Specifications, Group 3 – Sludge Processing* (2009b)

Taricska J. R., Long D. A., Chen J. P., Yung-Tse H., Shuai-Wen Z., *Anaerobic Digestion* in Wang L. (Editor), *Biosolids Treatment Processes* (2007), Humana Press, New Jersey

United States Energy Information Administration, *Form EIA-923 Power Plant Operations Report, Renewable Energy Consumption and Electricity Preliminary Statistics 2009*, http://www.eia.doe.gov/cneaf/alternate/page/renew_ energy_consump/table3.html, accessed online December 2010

United States Environmental Protection Agency (USEPA), Municipal Environmental Research Laboratory, *Technology Assessment of Solar Thermal Energy Applications in Wastewater Treatment* (1982), EPA-600/2-82-006, Cincinnati, Ohio

Water Environment Research Foundation, *State of Science Report: Resource and Energy Recovery from Sludge* (2008), Global Water Research Coalition

Weiland P., *Biogas Production: Current State and Perspectives*, Journal of Applied Microbiology and Biotechnology (2010), 85:849-860

Yuan S., Zheng Z., Mu Y., Yu X., and Zhao Y., *Use of Gamma-irradiation Pretreatment for Enhancement of Anaerobic Digestibility of Sewage Sludge*, Frontiers of Environmental Science and Engineering China (2008), 2(2):247-250